THE METASTABLE FLOW OF LIQUID WATER

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SYMBOLS

A_2	downstream area of nozzle, ft^2
P_1	upstream gage pressure, $lb_f\ in^{-2}$
P_2	downstream gage pressure, $lb_f\ in^{-2}$
P_{sat}	saturation pressure, $lb_f\ in^{-2}$
P_t	throat or discharge pressure, $lb_f\ in^{-2}$
t_1	upstream temperature, ^oC
t_2	downstream temperature, ^oC
Q	flowrate, $ft^3\ min^{-1}$
g	gravitation constant, 32.2 ft sec^{-2}
h	pressure differential, ft of water
p	pressure differential across nozzle, $lb_f\ in^{-2}$
v	velocity, ft sec^{-1}
V	specific volume, $ft^3\ lb_m^{-1}$
Z	zeta function for total mass m = E + mPV - TS, Btu
ζ	zeta function for unit mass = e - Ts + pV, Btu lb_m^{-1}
ψ	psi function for total mass = E - TS, Btu
E	internal energy, Btu
e	specific internal energy, Btu lb_m^{-1}
S	entropy, Btu F^{-1}

SUMMARY

A literature survey indicates that the flow to be expected when passing a metastable liquid through a nozzle is identical with that obtained for the passage of incompressible fluid through the nozzle for the imposed pressure drop. The assumption is made that the density of the incompressible fluid is identical with that corresponding to the upstream conditions for the metastable flow.

Water in a metastable condition flowing through a nozzle was studied employing, first, a nozzle used by C. W. Gorton (1) at the Georgia Institute of Technology and, second, a two-dimensional nozzle with glass sides to permit flow visualization. The second nozzle was designed for an upstream water temperature of 300° F, a 15-psi pressure differential, and with an exit area of 0.0734 in^2. The nozzle assembly was constructed in three parts: an interchangeable nozzle-test section, the intake section, and the discharge section; the three main parts of the test section were brazed together as a unit.

A shadowgraph apparatus and its accompanying point light source were constructed. The light was directed normal to the direction of flow, and the density variations in the flow field were observed on a ground glass screen.

The flow of initially subcooled water was varied by changing the back pressure, holding the upstream pressure and the temperature fixed. For purposes of comparison the variation between the nonflashing and actual

flows was indicated as a function of the pressure differential across the nozzle. The experimentally observed metastable flow rates, when using the first nozzle, did not conform with the corresponding calibrated nonflashing flow for a nozzle flowing full of liquid water. The same effect was observed later in the second nozzle; this lack of agreement is explained as due to the formation of steam in the core of the flow. This steam formation was observed using the shadowgraph technique.

The results of this experiment did not substantiate assumptions made by J. F. Bailey (2) in his analytical work.

CHAPTER I

INTRODUCTION

Objective.--The object of the investigation was:

1. To check more closely C. W. Gorton's "Metastable Limit" with the nozzle used in his experiments trying various laboratory procedures.

2. To photograph the flow of water in a metastable condition through a two-dimensional nozzle so as to verify the assumption made by Dr. J. F. Bailey in his analytic formulation of the problem.

Survey of literature.--It is a necessary condition for the improved design of equipment that more be known about how a medium will react to various conditions imposed upon it while passing through its saturation states. (The medium investigated here is water.) For a set of two or more known properties the state of the medium to be considered in the design has usually been a stable one: liquid, gaseous (superheated: steam, Freon, etc.), or having quality. Experience has shown that when a fluid flows from a superheated or a liquid region into the two-phase region for stable states, the flow will, in many instances, surpass that which was calculated. This was found to be the case in work with steam traps and nozzles. A summary of these investigations was presented by C. W. Gorton (1). Before these investigations it was always assumed that a liquid such as water would always flash to steam during an expansion at the point where the downstream pressure reached the saturation pressure corresponding to the initial upstream temperature and that the flow would remain constant for increasing pressure differentials across the orifice or nozzle.

In 1951, J. F. Bailey (2) presented a report in which he formulated a coefficient of contraction of a liquid core which, when multiplied by the isentropic mass flow rate for negligible initial velocity, gave the actual flow rate. This formulation was made using the following assumptions:

1. Vapor begins to form when the saturation pressure is reached.

2. The vapor forms at the interface between the fluid and the nozzle.

3. The flowing fluid consists of a metastable liquid core surrounded by an annular ring of vapor.

4. The mass of vapor discharging from the nozzle is negligible in comparison with the mass of liquid.

5. The change in temperature of the liquid core as it passes through the nozzle is negligible.

6. The velocity and pressure are uniform throughout any cross section of the fluid stream.

In an attempt to verify the first three assumptions a two-dimensional nozzle was designed and built. (See figures 17-21.) The last three involve measurements of the properties and quantities of the metastable core and surrounding vapor. Such measurements are impractical due to the fact that a metastable state will not persist in the presence of a finite disturbance due to the probe that would be required. (See General Discussion, Part II.)

In order to design the nozzle and photograph the flow, a survey was made for suggestions from past experiments preferably with water as the fluid under consideration.

Many studies have been made using water as the medium flowing in open channels and photographs have been made of flow of water around an object either under the water or at the surface of the water. These procedures are objectionable because (a) the techniques cannot be applied to flow between boundaries such as in a nozzle, and (b) a water-air interface is required.

S. E. Penner (3), in studying the flow both through and around a rectangle constructed of small plastic cylinders (analogous to flow through fabric), used immersion oil at room temperature for his fluid. The plastic model was placed in a horizontal methacrylate plastic (Plexiglass) tube and the oil, which was also translucent and of the same refractive index as the Plexiglass, was forced past the model. Air was introduced into the oil before the plastic fibre-model to distinguish the flow. Light from a 500-watt projection lamp was passed through a collimating lens (He found that a carbon arc was unsatisfactory.) and focused upon an adjustable slit using a cylinder lens. Light from the slit was collected by another adjustable cylinder lens and projected in a horizontal sheet (1/16 inch thick) parallel to and in the same direction as the flow. The dispersion of light by the air bubbles formed an image for the camera whose axis was perpendicular to the direction of flow. Here again the oil was kept in a stable liquid state. The introduction of air bubbles or other foreign matter into water in a metastable condition would contribute to the destruction of the condition. (See Discussion, Part II.)

Prandtl (4) discussed in great length various techniques for observing and photographing fluid flow. It was found that the flow of water can be shown in many cases by inserting colored water of the same specific gravity, such as potassium permanganate or certain kinds of analine dyes dissolved in a small amount of alcohol. Skimmed milk and aluminum particle suspension have been successfully used. The sharp illumination of oil droplets (a mixture of olive oil and nitrobenzal) with a thin sheet of light under an angle of 90 degrees with respect to the direction of fluid motion makes the drops clearly visible. Here again, however, a foreign material must be added to the test water.

Much work has been done and is currently being done on the study of air flow around or leaving a model of some sort. Vast quantities of reference material can usually be found in aeronautical literature. Some of the early investigators were Ewald, Poschl, and Prandtl (5). Photographs were made by using either a Schlieren or a shadowgraph apparatus. Both methods incorporate the fact that, as light passes through the object and is thrown on a screen or photographic plate, the individual parts of the image will appear light or dark according as the density of the object decreases in a given direction.

The principle upon which the Schlieren (6) depends is the change in illumination of a point in the image due to a small deflection of the rays in passing through the subject, as detected by a knife edge placed at the focal point of a lens located after the subject. Such a small deflection may be caused, in the simplest case, by a weak prism. A density gradient in a medium will produce exactly the same effect as a prism. The illumination of the image is a function of the first partial derivative of the density with respect to any direction perpendicular to the light source axis.

For a shadowgraph the illumination is a function of the second derivative of the space rate of change of density. The shadowgraph is the simplest optical method for observation of sharp density variations in a flow. In this system a parallel beam of light from a small intense source is passed through the fluid field and made to fall directly on a screen. A sharp shadow image will be produced only by high curvatures in the density field, as, for instance, through a shock wave or at an interface between two phases.

Stodola (7) experimented with steam leaving a nozzle section to study condensation of the jet. A pencil of light was shown in the direction of flow and photographs taken successfully with the camera's lens perpendicular to the direction of flow. The light wource was placed first downstream and then upstream of the nozzle. Prandtl's air jet photographs were also shown in which a high-intensity light source was placed upstream and downstream of the nozzle for photographs, and perpendicular to the direction of flow for shadowgraphs or Schlierens. In these cases only the steam or air leaving the nozzle was investigated except in only one case where Prandtl photographed steam flow through a nozzle with glass sides.

J. I. Yellott (8) studied the failure of steam to condense when the saturated condition is reached in an expansion (the metastable condition for steam). He was concerned in part in the determination of the Wilson Line, which indicates the condition where condensation actually occurs, and in the measurement of the size of the drops which are formed when flowing steam condenses. A nozzle with one transparent side was used. Brass nozzle blocks were bolted to the sides of a cast iron channel. The glass plate which constituted the top of the nozzle was clamped tightly to the channel with rubber gaskets over the nozzle blocks to prevent leakage.

Here the gasket material formed a part of the actual free flow area of the nozzle. A slit of light was passed in the direction of flow along the nozzle axis. Pressure and temperature traverses were made along the nozzle by means of a thin search tube.

A current review of a forthcoming book by Prof. Neil Bailey (9) offers the following observations on experiments with liquid flow through straight-walled ducts: below a pressure ratio of $P_1/P_t = 3$, where the kinetic energy ratio $N = v/(2gPV)^{1/2} = 1.0$, the duct flowed full of liquid. At or near $N = 1.0$, on increasing pressure ratios, the flow broke clear of the walls accompanied by a high-pitched whistling indicating instability. Reducing the pressure ratio carefully to a value less than 3.0, the jet remained separated for a time in a metastable state. (What the author meant here was that the medium was in a state of metastable equilibrium, since saturation conditions were not mentioned in the presentation. It is not to be confused with the supersaturated liquid discussed in this report.) In the range just below $P_1/P_t = 3.0$ the tests show instability.

This literature survey allows the following conclusions:

1. Because of the properties of a medium in a metastable state of equilibrium, introduction of foreign matter into the water to aid in its visualization appears questionable.

2. Light shining in the direction of flow is only satisfactory as an aid for observation when foreign matter is introduced into the system, and when condensation droplets or evaporative bubbles are present to diffract the light ray. This method further increases the complexity of construction of the test equipment.

3. A shadowgraph or a simple photograph of the flow separation

utilizing the reflection of light from a possible water-vapor interface can be made.

4. A two-dimensional nozzle can be constructed which would have glass on both sides of the nozzle and which features the testing of various interchangeable nozzle combinations and various nozzle flow areas.

5. Pressure differentials should be impressed both in an increasing and decreasing manner.

CHAPTER II

A DISCUSSION OF THE PROPERTIES OF THE METASTABLE MEDIUM (10)

In 1873 van der Waals proposed an equation of state which is usually written as $p = RT/(V - b) - a/V^2$ where a and b are constants for a given substance; the p - V plot of a typical isotherm is shown in figure 1. The portion of the curve cd represents unstable states and, therefore, states that cannot exist in nature. The states on the locus ab and ef are stable liquid and vapor states, respectively; bc and de represent metastable liquid and vapor states, respectively. Except in the unstable region,

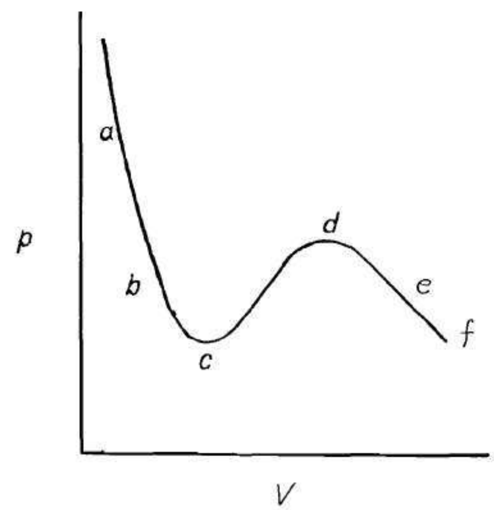


Figure 1. p - V Diagram for van der Waals Gas

$\partial p/\partial v)_T < 0$, which is necessary for stability of a substance. Thus, liquid water in a metastable condition is superheated water or water whose pressure is lower than the saturation pressure corresponding to its temperature.

Stability requires that for a given system $\Delta E)_S > 0$, $\Delta S)_E < 0$, $\Delta \Psi)_T > 0$, and $\Delta Z)_{P,T} > 0$. Where stability demands a constant pressure, all are equivalent to each other. The last one is useful to show what one might expect on a p - ρ diagram of the van der Waals isotherm. All letters match those of figure 2. A metastable state is stable for infinitesimal

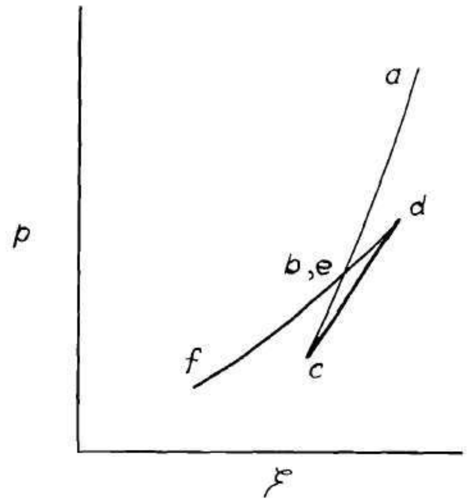


Figure 2. p - ρ Diagram for van der Waals Gas

disturbances and unstable for finite ones. Finite disturbances can be mechanical, such as the introduction of a foreign material to form the nucleus for condensation or to effect the formation of bubbles in the evaporative process, air bubbles, excessive vibration, quick changes in the pressure differential across a nozzle, and search tubes. Another finite disturbance is constituted by the formation of a bubble large enough into which the superheated liquid might evaporate. This size bubble will have a pressure less than the vapor pressure corresponding to a given ρ and the variation will be one in which $\Delta Z)_{P,T} < 0$.

An infinitesimal disturbance is caused by a small bubble formed in the liquid. Its pressure will be greater than the pressure for the particular ρ, and a possible variation from the metastable liquid would be one for which $\Delta Z)_{P,T} > 0$. The vapor in this bubble would condense back to liquid.

Therefore, finite disturbances will cause boiling and a definite change to a more stable state.

CHAPTER III

APPARATUS

The design of the two-dimensional nozzle.--According to Gorton's results, raising or lowering the initial pressure for a given back pressure, i.e., changing the rate of flow through the nozzle, doesn't affect the pressure difference between the saturation pressure corresponding to the particular water temperature and the back pressure at onset of the deviation of flow (the metastable limit).

Accordingly, a new nozzle was designed for the greatest possible area A_2 using the approximate relationship $A_2 = Q/60(2gh)^{1/2}$. This calls for the largest practical flow and water temperature, or the smallest possible pressure differential across the nozzle for which the deviation from calculated flow will occur. The nozzle was designed, therefore, for the highest temperature previously run, 290° F, which was assumed to be the limiting temperature for the existing heat exchanger. Thus, since Gorton's highest pressure differential was 11 psi, the nozzle was designed on a basis of 15 psi differential as stated in the preceding paragraph.

These maximum conditions were chosen with the thought in mind that areas, pressures, and temperatures might need to be changed in the actual experimentation.

A flow of 3 GPM and a 10° F temperature rise were the design conditions used as a basis for selecting the 6-KW heating element employed as a vernier temperature control. Later the 10° F control was sacrificed in favor of increased flow; 10 GPM for a 3° F Δt was used in the final selection of the throat area (0.0734 in.^{2}).

To benefit the visual observation of flow, the outlet cross section 0.18-by-0.407 inch was chosen. The nozzle inlet area was established by the choice of nozzle radii. The cross-sectional area of the approach section was made larger than the largest nozzle inlet cross-sectional area; this determined the height of the approach and discharge cross section. (For final dimensions see figures 16 and 20.) The 3/8-inch plate glass observation panels were chosen both for strength and for the ability to withstand reasonable thermal requirements. They were held firmly in place by wood blocks and iron angles bolted to the frame. (See figures 16 and 17.) The duct was designed for the same type of brass-to-glass contact around the edges as against the nozzle sections. This contact between the glass and the duct and nozzle was the most critical point in running the tests. Thin rubber gaskets were finally used and the nozzle blocks extended.

Four brass blocks 5-by-7/8-by-7/8 inch were machined to provide a 1/32-inch frame against which the glass might seat. Two thin brass bars 3-3/4-by-1/4-by-0.18 inch were machined to conform with the required dimensions and holes appropriately drilled to accomodate the NC 2-56 machine screws, which were to draw the threaded nozzle blocks against the test section. All parts were finally finished with a fine file.

Two brass nozzle blocks were machined to a thickness of 0.18 inch. The nozzle design was traced on the block, cut out with a band saw, and finished with a file and emery cloth for a smooth finish. Two holes were drilled and threaded in the nozzle base for the machine screws. (See figure 20.) The number and the size of the screws were chosen for convenience and strength.

Test section pieces were then assembled, using silver solder, and the finished product was then brazed to a 5-inch black malleable iron pipe cap at either end. A 4-1/2-by-3/16-inch slit was first cut across the face of the cap to match the entrance or discharge area of the test section. This finally produced a unit that was very versatile in that it could be attached easily to any size piping at either end through the use of reducers or bushings. The unit was attached to Gorton's original 2-inch pipe approach section by the use of a 5- to 2-inch bushing. (See figure 19.)

Shadowgraph.--The shadowgraph apparatus (See figures 21 and 22.) originally called for an intense, point light source and a lens to parallel the light before it passed through the object and then onto a screen. The point light source was an original design by the author. A 300-watt, clear glass, incandescent electric light bulb was placed an arbitrary distance from a lens of the same type called for above (4-inch diameter, 10-inch focal length, reading glass type). Various distances were tried so that the light being focused on a smooth object placed at the lens' focal length gave the brightest possible image of the resistance element in the light bulb. To obtain a sharp focus, the bulb should have theoretically been placed an infinite distance from the lens. A distance of six feet was found to be satisfactory. The light was directed through tubing made of heavy manila paper which was first painted black and then covered with lampblack for a dull finish and for minimum practical light reflection along the tube. The tube prevented light from being reflected from the surroundings. A strip of brass shim 0.02 inch thick and one inch wide was drilled with various sized holes one inch apart and mounted so that the strip could be pulled through a friction-type holder and the various sized holes tried for optimum results. This assemblage provided the required point light source.

The second lens was placed on the other side of the point source and its distance from this source adjusted for the best spot of light on a ground glass screen. The screen-lens distance was also adjusted for the clearest picture of the object.

Since the test section was approximately 5.5 feet from the floor, a long wooden "horse" six inches wide was constructed to accomodate the optical system, as well as to give some support to the test section. (See figure 22.)

All final supports, excepting the laboratory-type test stands to hold the lenses, were constructed from plywood. C-clamps were used to hold the supports and test stands in position.

General assemblage.--Drawings, photographs, and a flow diagram of the apparatus are given in Appendix C. Any apparatus used by C. W. Gorton and described in great detail in his thesis will only be briefly mentioned here to provide for continuity in the discussion.

All water was obtained from the city water supply of Atlanta, which at this location was at a pressure of approximately 85 psig. A horizontal overhead main in the Steam Laboratory provided the supply point. The water ran through an overhead riser, a 3/4-inch globe valve, a 0- to 11.5-gpm Fisher and Porter Flowrater calibrated in centimeters, and another vertical riser to the water tube condenser, which was used to provide an initial hot water supply.

Laboratory steam was used in the converted condenser to heat the water. Fifty psig was considered a maximum safe pressure to be used. The condensate flowed through a 50-pound trap and to a drain located in the floor.

An NWH 362 Chromalox Circulating Water Heater made by the Edwin L. Wiegand Company was installed after the condenser for vernier temperature control of the water flowing through the approach section. This heater was rated at 6 KW, 230 V, 1 phase and was provided with a 1-inch inlet pipe near the bottom, a 1-inch outlet pipe near the top; three heating elements connected in parallel by copper bus bars across the terminals, a 3/4-inch drain pipe on the bottom, a terminal cover, and support taps for machine screws. The heater was installed in a vertical position with the terminals up, as instructed, and supported from the floor with a vertical 1/2-inch pipe. The power was supplied through a Powerstat with two number 12 weatherproof wires attached to each side of the paralleled heating elements and was protected by a 30-ampere fuse. Two 1-inch globe valves were placed before and after the heater and a 1-1/2-inch heater by-pass globe valve was installed in the line rising from the condenser.

A voltmeter and an ammeter were placed across and in the line, respectively, to determine the wattage to the heater. The voltmeter was a 0-30 V Weston A. C. Voltmeter, and the ammeter a 0-75 ampere A. C. Ammeter; both were calibrated before installation. A Powerstat (variable transformer) was used to vary the wattage to the circulating water heater. This Powerstat was a Superior Electric Company Powerstat (Autotransformer) with the ratings as follow: Type 1256, primary 230/115 V, 1 phase, 50/60 , output voltage 0-0.270, maximum output 28 amps, 7.5 KVA. It was connected as instructed with the power supply lines connected to the "inlet" and "common" terminals, the lines to the heater connected to the "common" and "230-V outlet" terminals. Horizontal mounting was used, although a template was provided for vertical or panel mounting.

The original power source was located in the starting box for a weir-drain-pump located in the Mechanical Engineering Laboratory, a 220-volt, 3-phase supply. Number 12 weatherproof wires were connected across two of these terminals and run through a switchbox mounted on the wall above the starting box. This was the 220-volt, 1-phase supply for the Powerstat and heater.

After leaving the circulation heater, the water went to the top of a 2-inch pipe approach section, at which point an air bleed was provided to rid the system of entrained air. The air-bleed line consisted of a 3/8-inch pipe and globe valve.

The pressure taps were made from 1/4-inch standard pipe. The upstream pressure was recorded using a 0- to 100-psig Bourdon tube gage manufactured by the Crosby Steam Gage and Valve Company, and the downstream pressure was recorded using a 0- to 30-psig Bourdon tube gage manufactured by the Kewanee Boiler Corporation.

The thermocouple wells used with the two-dimensional nozzle were machined from 1/2-inch brass stock to take a 3/8-inch thread. A 3/16-inch hole was drilled to within 1/4 inch from the nonthreaded end and a 1/32-inch hole drilled the rest of the way. The iron-constantan thermocouple lead was inserted in the threaded end and made to project slightly through the 1/32-inch hole, where it was silver-soldered in place. The well was threaded into a 1/8-by-1/2-inch bushing, which in turn was threaded into a 1/2-inch threaded hole in the approach or discharge section.

The thermocouples were connected through a two-pole, double-throw switch to a direct-reading Leeds and Northrup Potentiometer ranging from 0°-800° C for iron-constantan. Three No. 6 dry cell batteries were connected in parallel to the potentiometer to balance the circuit.

The approach and discharge sections were assembled and placed in the line, making use of unions to facilitate the removal of the test section for repairs or other changes. A 1-inch pipe connected the downstream side of the test section to a condenser. The test and cooling water left the system through a drain located in the floor near the downstream condenser.

Photographs were made by Messrs. Garrett and Prouse of the Georgia Tech Engineering Experiment Station with a Graphic View camera placed 22.5 inches from the ground glass screen. A 10-second exposure was made, using an ektar lens, f 7.7, and 203 mm focal length.

CHAPTER IV

TEST PROCEDURE

The nozzle pair was bolted to the test section, with the angle irons left in place for structural strength. The gasket material, glass, and wood were placed in position, removing only that angle iron which was necessary to accomplish this assembly. The glass was pressed in place by tightening the bolts.

The potentiometer was balanced following standard instructions for the instrument. The condensing water was turned on and power supplied to the Powerstat while set at 0 per cent.

The valve controlling the city water supply to the overhead main was turned on, and a small flow of water was allowed to flow through the apparatus. The air-bleed valve was opened slightly, and the circulation-water-heater by-pass valve was closed; the other two valves to this heater remained opened.

The valve draining the main steam lines in the Mechanical Engineering Laboratory was partially opened, and the valve in the steam line from the heating plant was opened slowly. Just after this valve a pressure-reducing station was located and after which there was a valve to the main laboratory steam line. This second valve was opened slowly, sending steam to the laboratory steam header. When steam began to leave the drain line, its valve was closed to a "cracked open" position and the valve after the reducing station was regulated to hold approximately 60 psig pressure in the laboratory main line.

The valve in the line connecting the heater (converted condenser) to the laboratory steam main was partially opened, and the valve just after the blocked-off air ejector was "cracked open" to drain the condenser shell. A flow of cooling water was started in the downstream condenser.

The upstream temperature T_1 was observed for the necessary temperature rise; the air-bleed valve was closed at 100° C. The steam pressure in the shell was then usually reduced and the pressure differential across the nozzle established for the beginning of the first test. The final upstream temperature was reached by increasing the setting on the Powerstat with care taken not to exceed the rating of the water-circulation-heater as indicated by the ammeter and voltmeter. Experience with the apparatus was the main factor in controlling the condenser shell pressure. The barometer reading was taken and, when the temperature T_1 was constant for at least one minute duration, the data were taken in the following order: P_1, P_2, cm, T_1, T_2, P_{cond}, volts, amps. Although only the first five were basically essential data, the last were taken for the protection of the apparatus.

P_2 was always above the saturation pressure at the start of each run so that liquid was on both sides of the nozzle. As P_2 was slowly changed (increasing or decreasing) it was usually necessary to readjust P_1 slightly by manipulating the city supply valve before the rotameter. The manipulation of this valve directly affected the flowrate. All changes in pressure were made very slowly so as not to upset the desired state of the water in the nozzle. The pressure drop across the nozzle was slowly increased in increments of 1/2 to 1 psi, keeping P_1 and T_1 constant. When T_1 changed about 1/2 degree, the p was decreased to a point where P_2 was again above the saturation pressure for T_1. After T_1 was brought back to normal, the pressure differential was slowly arranged to where the run was previously interrupted.

When the runs were completer, the heating units were shut down and the flowrate increased to decrease T_1 below 100° C. Then a low flowrate was used with the air-bleed line partially open to slowly cool the plate glass down to room temperature.

CHAPTER V

DISCUSSION

Gorton's Nozzle

First, the nozzle used in Gorton's experiment was recalibrated (See figure 9.); two experimental runs, each of two tests, were then conducted. Each run was carried out by, first, setting the lowest pressure differential across the nozzle by the use of the water supply valve and the back pressure valve and, then, bringing the upstream water to a temperature of 259.6^{o} F. From this condition, the pressure differential across the nozzle was increased as far as it could be in increments of approximately 1 psi. This point of maximum pressure differential was then used as the starting point for a second test in which the pressure differential was decreased in increments of 1 psi.

A second run was made in exactly the same manner as the first.

The limit of metastability was found in the following way: the gage readings were corrected using the calibration curves and the various pressure differentials across the nozzle established. The calibration curve for the flow of water through the apparatus and the flow readings taken during the test were corrected for the temperature used in the tests. These temperature corrections were necessary in both cases since the flow-rate was located before the heating units and only recorded flows at city water temperature. The calibration curve correction resulted in a new calibration curve for the flow of 259.6^{o} F water through the apparatus. For a corrected back pressure, the pressure differential Δ p was obtained and this differential was used to find the value of the fully flowing nozzle on the new flow calibration curve. A complete sample calculation is given as Appendix B. ΔP was plotted versus the nonflashing flow and the actual flow. The point at which the actual flow first deviates from the nonflashing flow is called the "metastable limit." (See figures 9 and 11.) Unless P_1 was held absolutely constant, back pressure could not be used for an abscissa on the graph.

The flow of metastable water was obtained in most cases and corresponds to that portion of the curves between the saturation pressure corresponding to the upstream temperature and the metastable limit. It was noticed on the test number 3 (See figure 10 (a).) that, when the back pressure was being decreased, there was an immediate flashing to steam at the saturation pressure and the line runs horizontally, signifying steam flow. Theoretically, this line should have remained horizontal for the rest of the run, but in adjusting for a falling initial pressure by opening further the city water supply valve, conditions were established which forced the flow back toward the fully flowing nozzle line. This was later found to be the case with the two-dimensional nozzle. Near the end of this test the points were back on the line and proceeded to deviate at the metastable limit. The same tendencies also prevailed on test curve number 1. (See figure 10 (a).) It was shown by the results here that the upstream pressure, although hard to control with the particular apparatus at higher temperatures because of a lag between manipulation of the water supply valve and the reaction on the upstream pressure gage, should be kept as constant as possible at the predetermined pressure. The back pressure was quickly manipulated by slight adjustment of the back pressure valve. In the metastable water flow region this gage fluctuated constantly and quite rapidly. On the first run a mean value was recorded, and on the second run the extreme values were recorded. It was believed at the time that the fluctuating gage was a characteristic of metastable flow through the system.

Test curves number 2 and 4 (See figure 10 (b).) are the graphical results under conditions for which the pressure differential was decreased by slowly increasing the back pressure. These tests indicate that a metastable condition is much more likely to exist during a condition of decreasing pressure differential. The reason given for this is that, as P_2 is increased, the back pressure tends to increase P_1; this resulting increase of P_1 tends to bring the flow to conform with the calibrated nonflashing flow line on the graph, as was indicated in tests 1 and 3.

Two-Dimensional Nozzle

Experimental results.--At the outset of the experimentation the main problem was to seal the test section against leakage. Permatex Nos. 1 and 2 were tried; No. 2 was quickly eliminated; No. 1 (fast-drying, hard-setting) was found to be neither fast-drying nor hard-setting in this apparatus, even after baking it with an infrared lamp for 30 minutes and leaving it to sit for 36 hours. A bakelite compound was tried next, but it was brittle and would not stand exposure to hot water.

Rubber packing 0.036 inch thick was then tried, using a pattern as shown in figure 20. This procedure changes the nozzle area, however, and the packing material was discarded as being too hard. Finally, a soft black rubber gasket was used, together with a peripheral gasket of very soft white rubber. (See figure 20.) The original wooden blocks were widened to twice the thickness shown in figure 16, and the nozzle area was decreased (since the free flow area now was bound by both the gasket and the brass nozzle surfaces) by inserting rubber packing 0.07 inch thick between the nozzle base and the frame. A black rubber gasket, the dimensions of which were made to conform with the wooden blocks, was placed as a cushion between the wood and glass. Small C-clamps helped prevent deflection of the angle irons. This combination proved itself highly successful. The order of assembly was as follows: the white rubber gasket, the black one (A bit of mucilage helped hold these in place for vertical mounting.), glass, black rubber cushion, wooden blocks, and angle irons. (The C-clamps were finally placed in position after both sides were assembled.) A test procedure similar to that used on the first run was repeated here. The back pressure valve was always manipulated first, and the water supply valve quickly used to hold P_1 constant.

The results of this test, as indicated by the graphs of flow versus Δp, were consistant with the results of the other nozzle. After using this second nozzle and observing a vortex action in the discharge duct, the fluctuations of the downstream pressure gage on Gorton's apparatus (Gorton's pressure tap was immediately after the nozzle) were explained by the rapid and cyclic vortex actions taking place in the vicinity of the tap. Therefore, this would not give any significant indication of the condition of flow in the nozzle.

Visual results and trends.--By far the most significant results of this investigation appear as graphical summaries and the photographically recorded visual observations, the one tending to verify the other.

The literature survey indicates that the flow to be expected when passing a metastable liquid through a nozzle would be identical with that obtained at corresponding pressure drops for the passage of incompressible fluid through the nozzle, the assumption being that the density of the incompressible fluid is identical with that corresponding to the upstream conditions for the metastable flow. Although the tests came close to satisfying this indication, a series of experimental deviations occurred which at first were unexplainable with Gorton's nozzle but later clarified with the two-dimensional one. As can be seen in the graphs, figures 11 and 12, this agreement of flows was not obtained. Rather, the flow was lower than the incompressible flow for the same pressure drop and began to flow in favor of the flashing or steam curve up to the "metastable limit." Any scatter of points at low Δp's where $P_2 > P_{sat}$ may be attributed to (a) the lack of accuracy of the rotameter at low flowrates and (b) lack of adequate control of the pressures.

What was seen during the two-dimensional flow run was immediately unexpected but quickly explainable. At $P_2 > P_{sat}$ the field (the term "field" to denote the image of the water as it appeared on the ground glass screen) was clear both upstream and downstream of the nozzle excepting vortices on either side of the flow on the downstream side of the nozzle. (See figure 3.) Approximately where $P_2 = P_{sat}$, a faint cloudiness appeared in the field in the center of flow upstream and through the nozzle but not so much downstream of the nozzle. Small bubbles were seen leaving the tips of the nozzles and traveling quickly toward the vortices. A faint gray cone began to appear at each nozzle tip with apex at the tip and a center line about two degrees from the perpendicular wall of the water core. This cone was at first very light and would appear and disappear, indicating instability. (See figures 4 and 7 (a).) As P_2 was decreased ($P_2 < P_{sat}$), the greyness just above and in the center of the core grew darker and projected through the center of the core from above the nozzle downstream through its entire length. Further, the cones became darker and stationary. (See figures 5 and 7 (b).)

As P_2 was decreased to its lower limit, the grey pencil in the core center and the cones increased only slightly in dimensions but grew much darker. Near the end of the lower limit of P_2 there was no discernible change in the characteristics of core and cones. (See figures 6 and 7 (c).)

An attempt to make the nozzle flash resulted in a sudden, discontinuous field of vision on the downstream side with a very slight liquid core projecting from the nozzle and some disturbance in the nozzle. Figure 8 shows the cevelopment of the flash.

The photography as shown was only effective in that it brought out the main outline of the regions (probably because of too long a time exposure) but does not show in great detail that which was predominant on the ground glass screen. Sketches were made (See figure 7 (a), (b), and (c).) to show more fully what actually appeared as described above and are in a one-to-one correspondence to figures 4, 5, and 6.

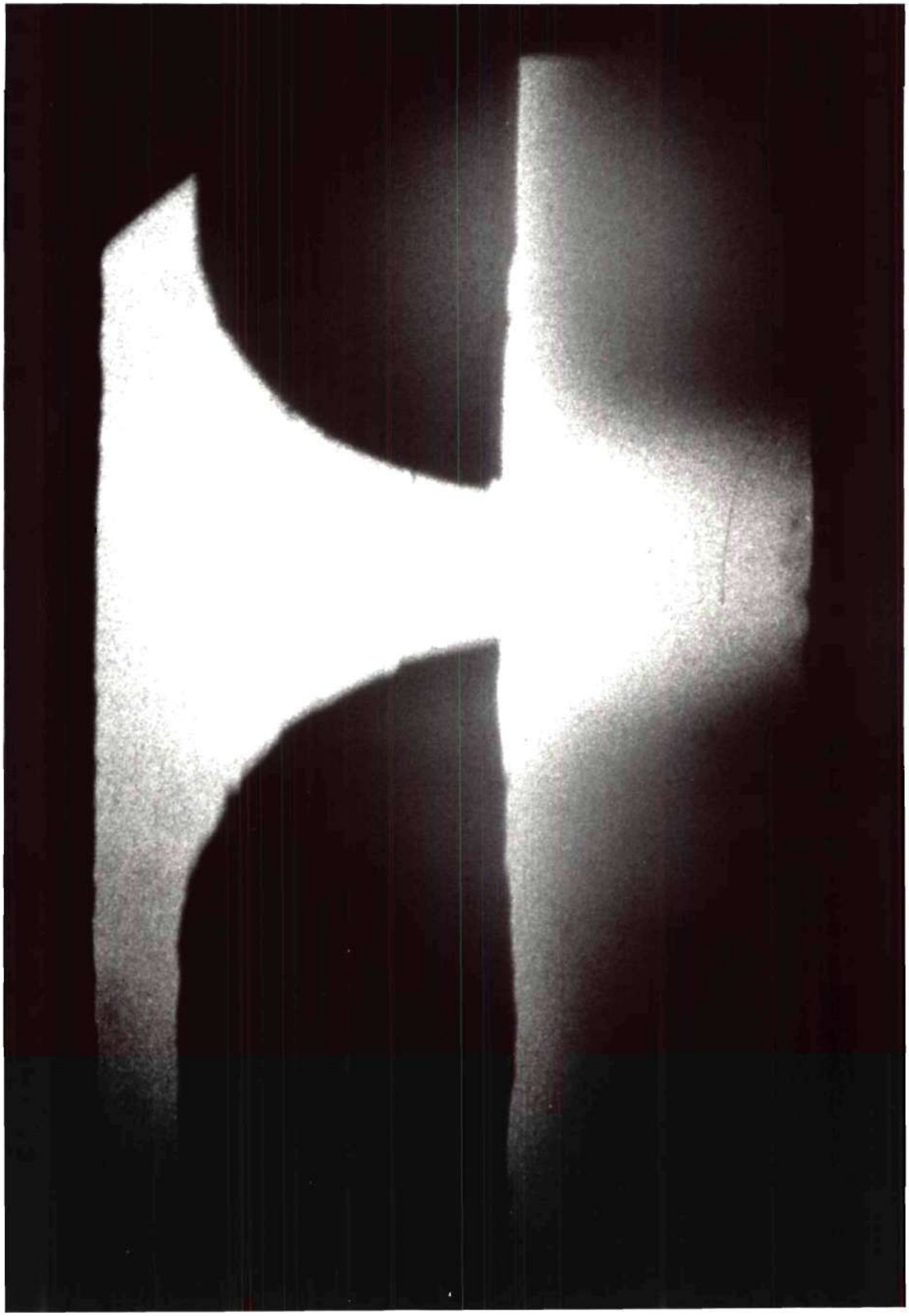


Figure 3. Fully Flowing Nozzle $P_{sat} < P_2$

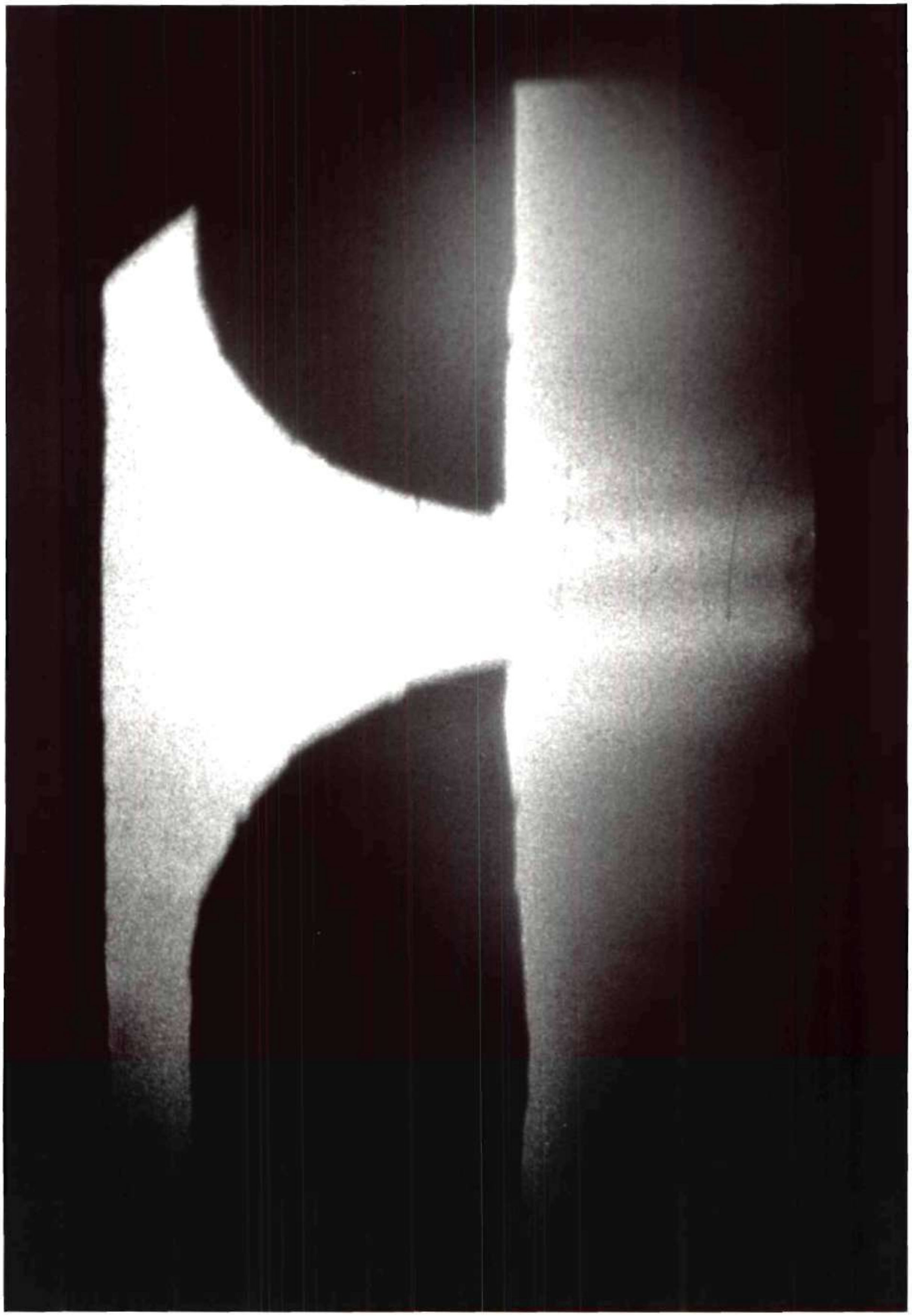


Figure 4. Flow at $P_{sat} = P_2$

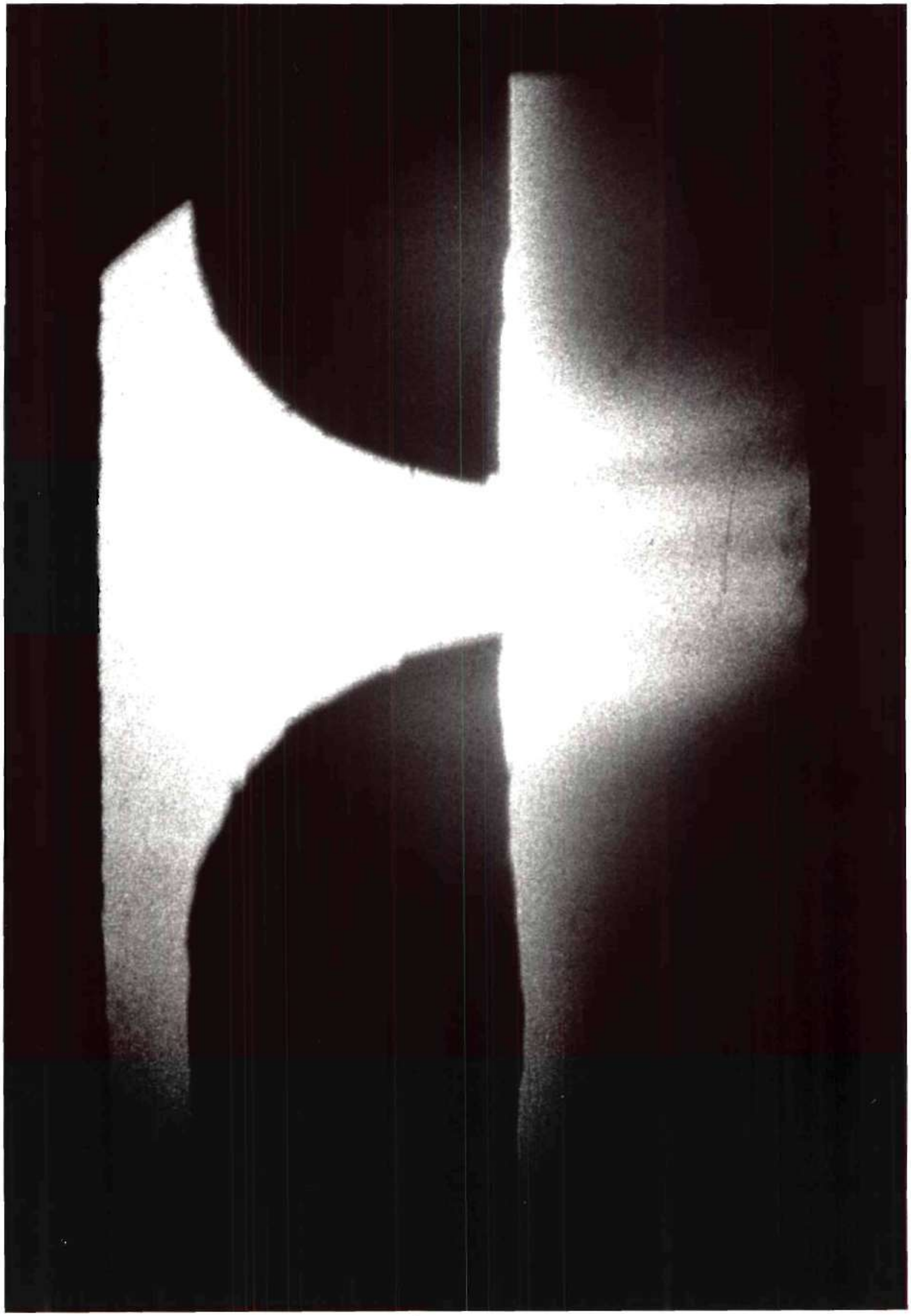


Figure 5. Flow at $P_{sat} > P2$

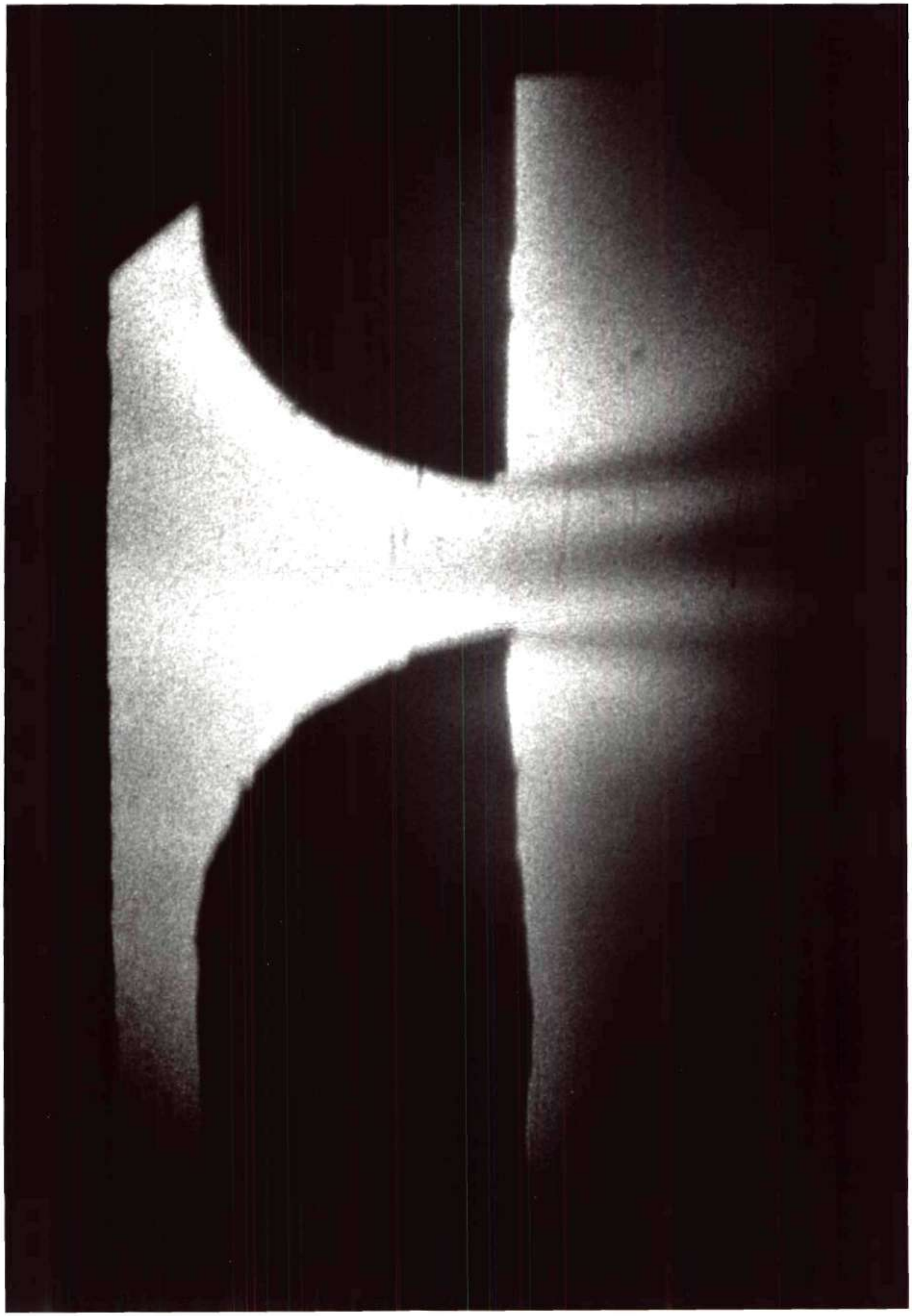
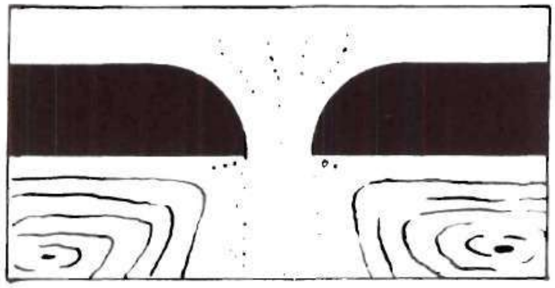
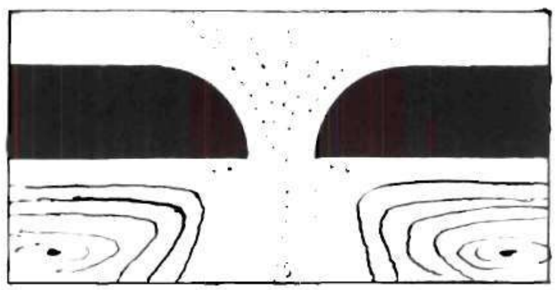


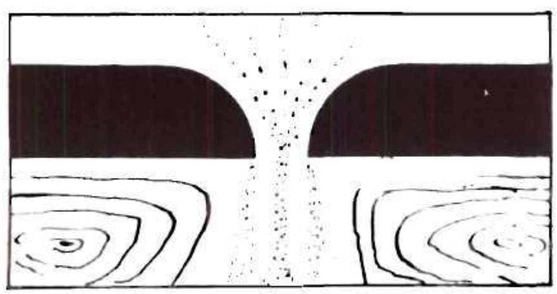
Figure 6. Flow at $P_{sat} >> P_2$



(a)



(b)



(c)

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Sketches of Figures 4,5,6.

Drawn by: Arthur J. Shane Date: 8-7-52

Figure 7

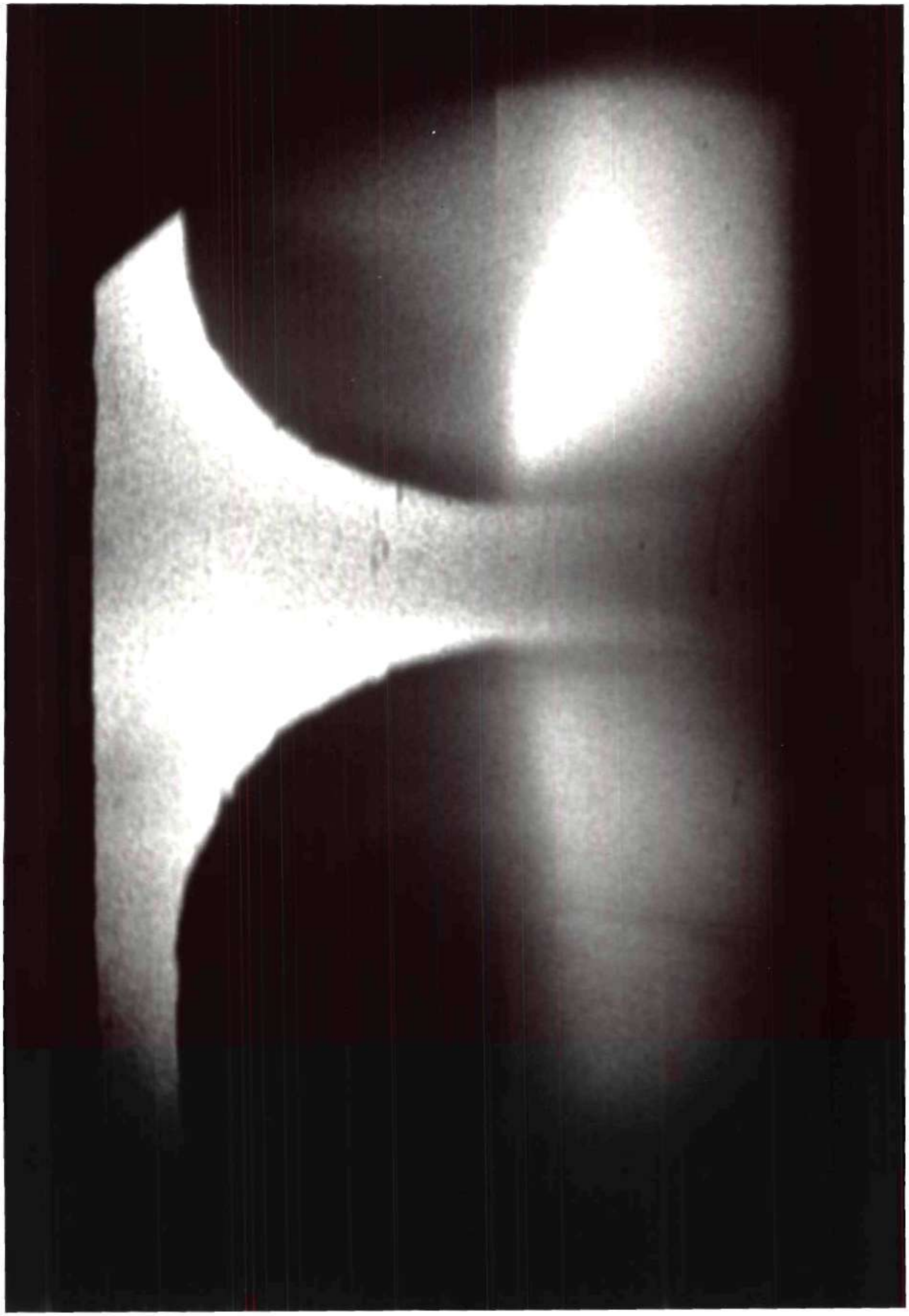


Figure 8. Flow Just Before Flashing

Calibration

Both gages were calibrated in five-pound intervals using a dead weight tester. (See figure 23.) The flow system was calibrated by adjusting the pressure differential in the smallest practical increments. This calibration was carried out twice both by increasing and decreasing p's. The calibration was also roughly checked before each run for the metastable flow. (See figures 9, 12, and 13.)

The temperature-indicating system was calibrated from 30° to 100° C in an atmospheric pressure, heated water bath using calibrated standard thermometers.

All other operational instruments which had no bearing on the results of the test were calibrated for equipment protection only.

CHAPTER VI

CONCLUSIONS AND RECOMMENDATIONS

Design.--A two-dimensional nozzle can be successfully constructed using the gasket thickness as a part of the final designed nozzle width. Experience showed that a greater bearing area between the gasket and the test section would facilitate a more positive and more easily sealed apparatus. Probably a 1/2-inch frame around the perimeter would have been more successful in the beginning, although the before-mentioned final gasket combination worked very well after many attempts.

The recommendation is made that light sources of various intensities be tried in conjunction with a motion picture camera to record the full development of the flow. A stroboscope should be put in place of the light bulb to examine the flow for possible periodic changes such as the development and ultimate collapse of bubbles too small to create a finite disturbance and flashing.

Nozzles with radii varying from zero inch to approximately one inch should be tried. Each of these nozzles should have a straight-walled duct exit length attached after the nozzle varying from zero inch to one inch, and the discharged area and the upstream pressure should be varied to determine which combination more readily tends to provide the highest and lowest flowrate.

The water-circulation-heater should be placed just before the test section for more positive control of temperature. Located where it was, there was still a time lag between a change of setting on the Powerstat and a reaction on the potentiometer.

The control of upstream pressure should be made automatic.

Tempered glass is recommended as a replacement for the plate glass before going to higher temperatures.

Experimental.--The existence of vapor in the center of the flow is verified by the fact that a velocity-pressure change exists across the nozzle. Where the velocity was theoretically zero and the pressure was highest at the walls of the nozzle, no vapor existed. The velocity was the greatest at the center, and the resulting pressure drop caused either vapor or a cloud of bubbles to exist there.

A fluctuating downstream pressure gage signifies the existence of vortices, with their accompanying pressure variations, in the region of the pressure tap and should be avoided if possible.

Until a pressure traverse is made in the flow region itself, there is still no assurance that a metastable condition exists; possibly the co-existence of stable liquid and vapor at saturation conditions.

A further study of the optical method used by Yellott might suggest that a similar method could be used for the qualitative observation of metastable flow of liquid water through nozzles.

APPENDIX A

EXPERIMENTAL RESULTS

Table 1. Flow Calibration for Tests 1 through 4.

Water Temperature = 32^{o} C

P_1	P_2	Δp	cm	P_1	P_2	Δp	cm
24.0	8.1	15.9	6.52	33.0	26.4	6.6	5.05
29.0	15.3	13.7	6.28	53.3	2.3	51.0	10.2
31.0	18.5	12.5	6.10	55.0	2.5	52.5	10.35
38.8	18.0	20.8	7.30	57.1	10.0	47.1	9.95
35.2	23.0	12.2	6.25	55.5	1.8	53.7	10.4
37.2	15.2	22.0	7.5	58.8	2.0	56.8	10.6
36.5	13.5	23.0	7.55	60.0	2.0	58.0	10.7
34.3	10.7	23.6	7.75	62.0	12.0	50.0	10.14
34.0	9.5	24.5	7.75	65.0	3.0	62.0	11.0
32.1	5.1	27.0	7.97	66.8	10.0	56.8	10.65
36.3	9.8	26.5	8.0	66.8	8.0	57.8	10.8
35.0	8.0	27.0	8.05	64.0	12.1	51.9	10.25
34.0	5.5	28.5	8.16	70.0	6.9	63.1	11.13
40.0	9.8	30.2	8.38	69.0	4.8	64.2	11.25
38.0	5.7	32.3	8.55	68.8	2.8	66.0	11.3
36.3	2.8	33.5	8.75	72.5	3.0	69.5	11.6
44.2	8.8	35.4	8.85	74.2	12.0	62.2	11.15
42.0	5.0	37.0	9.0	76.5	5.0	71.5	11.7
41.2	1.9	39.3	9.16	76.5	2.0	74.5	11.85
48.5	8.5	40.0	9.35	78.0	2.1	75.9	12.0
47.2	4.9	42.3	9.5	78.0	1.5	76.5	11.95
52.5	19.8	32.7	8.7	79.0	2.0	77.0	12.0
46.2	3.0	43.2	9.65	79.0	2.0	77.0	12.0
50.0	5.3	44.7	9.7	80.0	5.1	74.9	11.95
49.0	2.0	47.0	9.9	80.0	14.9	65.1	11.25
26.0	17.5	8.5	5.2	31.0	23.0	8.0	5.15
25.0	14.0	11.0	5.6	28.0	18.5	9.5	5.3
28.2	20.2	8.0	5.25	29.0	18.0	11.0	5.75

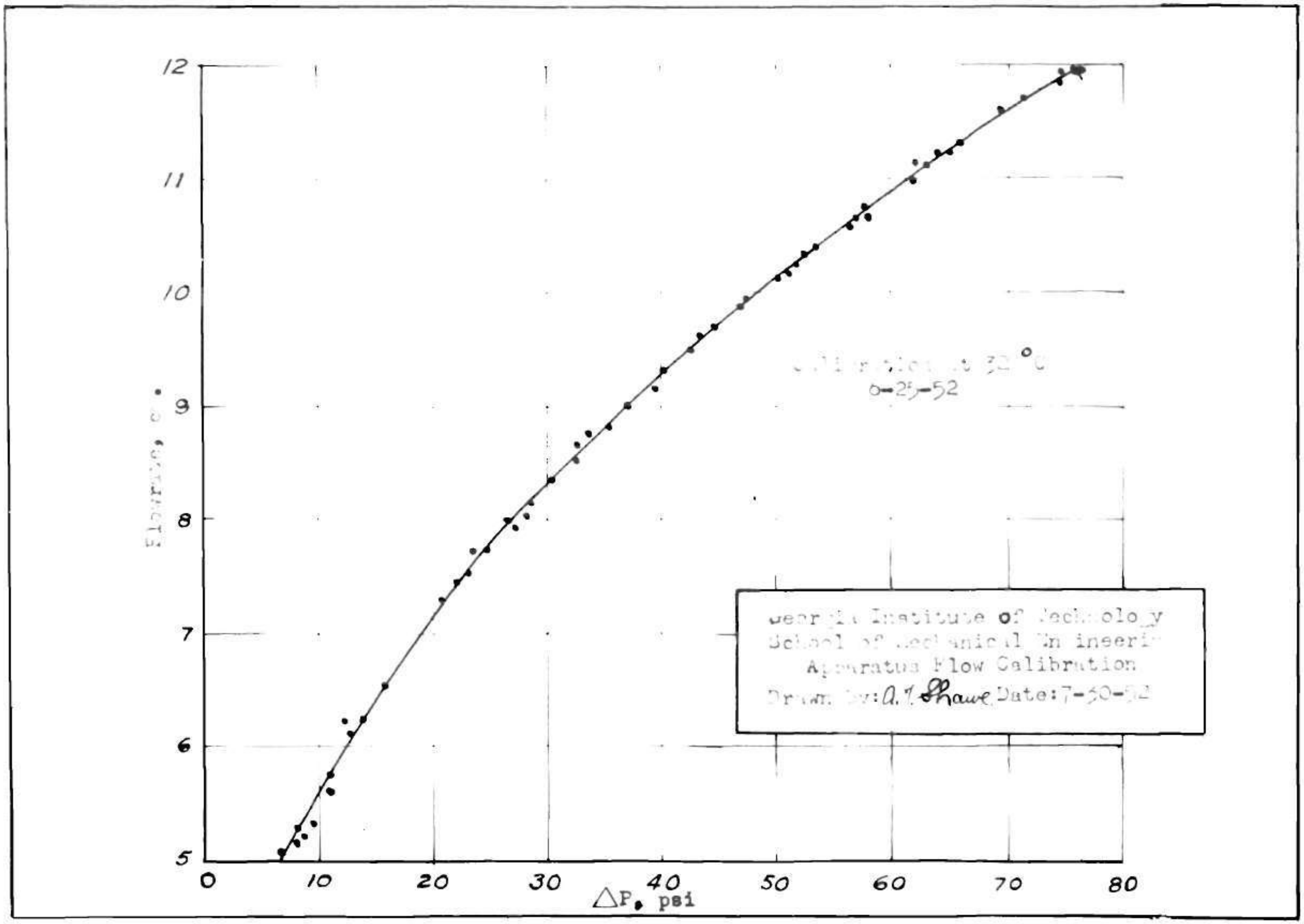

12
11
10
9
8
7
6
5
0
10
20
30
40
50
60
70
80
ΔP, psi
6-25-52
Flow Calibration

Figure 9

Table 2. Test No. 1.

T_1 Avg: 126.6° C = 260.0° F — $P_{saturation}$: 35.4 psia

Barometer: 14.3 psia — Date: 6-26-52

P_1 (psig)	P_2 (psig)	T_1 (°C)	Flow (cm)
30	22	126	4.80
30	21	127	4.85
30	20	126	5.00
30	19	126	5.60
30	18	126	5.55
30	16	127.5	5.60
30	15	128	5.60
30	14	126	6.00
30	12	127	6.55
30	11	127	6.60
30	10	127	6.60
30	8	127	6.65
30	5.5	126	6.75

Table 3. Test No. 2.

T_1 Avg: 126.6° C = 260.0° F

$P_{saturation}$: 35.4 psia

Barometer: 14.3 psia

Date: 6-26-52

P_1 (psig)	P_2 (psig)	T_1 (°C)	Flow (cm)
30	5.5	126	6.75
30	8	126	6.65
30	10	126	6.65
30	11	126	6.65
30	12	127	6.4
30	13	126	6.33
30	14	126	6.33
30	15	126	6.15
30	16	127	5.58
30	17	127	5.9
30	18	127	6.0
30	19	127	5.3
30	20	127	5.3
30	21	127	5.3
30	22	127	5.0
30	24	127	4.4

Table 4. Test No. 3.

T_1 Avg: 126.6° C = 260.0° F

$P_{saturation}$: 35.4 psia

Barometer: 14.3 psia

Date: 6-26-52

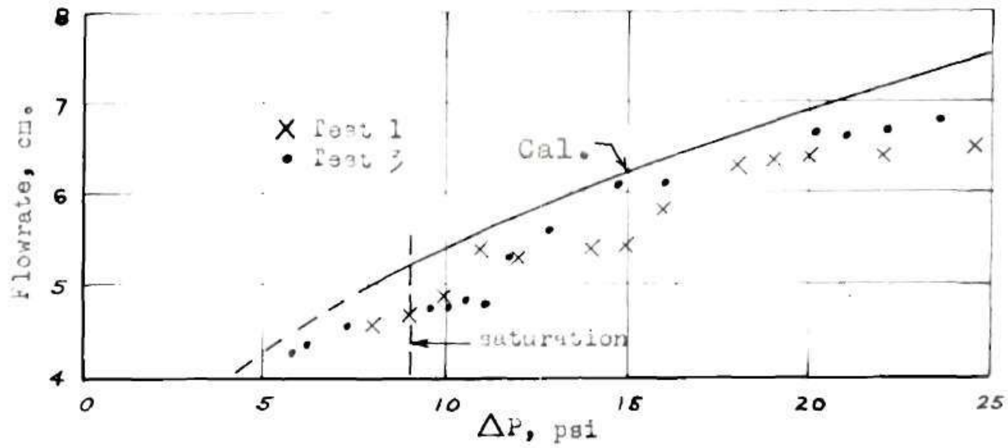
P_1 (psig)	P_2 (psig)	T_1 (°C)	Flow (cm)
30.8	25.2	127	4.4
29.0	23.0	125	4.42
29.1	21.0	125	4.7
30.0	21.0	126	4.92
30.0	20.0	127	4.9
30.0	19.0	128	4.95
29.2	18.5	127	4.98
28.0	16.6	127	5.48
28.0	15.7	127	5.75
28.6	14.8	127	6.36
29.2	13.8	127	6.33
30.0	10.0	127	6.95
30.0	9.0	126	6.88
29.9	7.9	127	6.95
30.0	6.7	126	7.05

Table 5. Test No. 4.

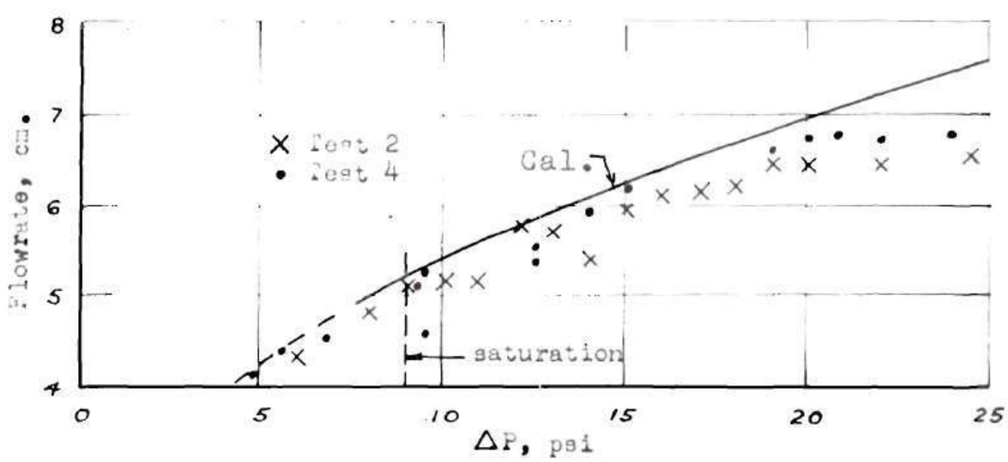
T_1 Avg: 126.6° C = 260.0° F — $P_{saturation}$: 35.4 psia

Barometer: 14.3 psia — Date: 6-26-52

P_1 (psig)	P_2 (psig)	T_1 (°C)	Flow (cm)
30.0	6.5	126	7.05
30.0	8.1	126	7.00
30.0	9.6	126	7.00
30.5	10.8	126	6.98
31.0	12.5	126	6.8
30.5	13.6	126	6.3
30.6	15.8	126	6.32
31.0	17.1	126	6.1
31.7	19.2	127	5.7
32.0	20.2	128	5.5
31.0	21.7	127	5.5
32.0	22.8	128	5.2
32.0	22.5	127	4.7
31.0	24.2	127	4.7
31.7	26.2	127	4.6
32.5	27.7	127	4.3



(a) Increasing the ΔP.



(b) Decreasing the ΔP.

Note: Calibration and data corrected to 1[illegible] °C.

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Data Trends: Tests 1 thru 4
Drawn by: A. J. Shawe Date: 7-31-52

Figure 10

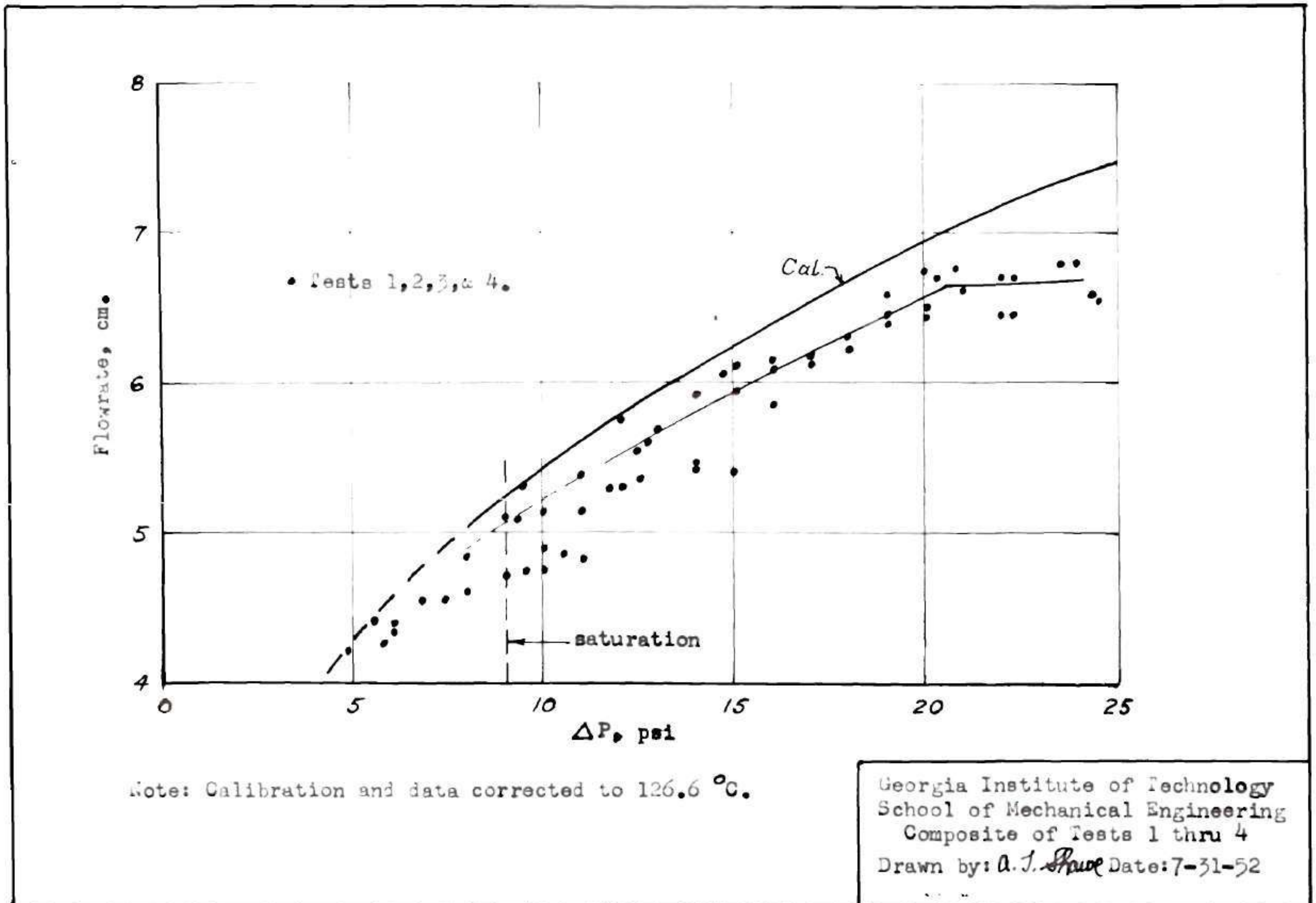

8
7
6
5
4
0
5
10
15
20
25
Flowrate, cm.
ΔP, psi
• Tests 1,2,3,& 4.
Cal.
saturation
Note: Calibration and data corrected to 126.6 °C.
Georgia Institute of Technology
School of Mechanical Engineering
Composite of Tests 1 thru 4
Drawn by: A. J. Rowe Date: 7-31-52

Figure 11

Table 6. Flow Calibration for Test No. 5.

$T_1 = T_2 = 31^{\circ}$ C

Date: 7-25-52

	P_1 (psig)	P_2 (psig)	Flow (cm)	P_1 (psig)	P_2 (psig)	Flow (cm)
Run 3	13.3	7.8	13.5	13.3	12.2	6.6
	(held	8.2	12.95		11.9	7.5
	constant)	8.5	12.85		11.5	8.4
		8.95	12.45		11.1	9.55
		9.3	11.8		10.45	10.45
		9.6	11.3		10.0	11.2
		10.0	10.95		9.5	11.95
		10.2	10.35		9.0	12.4
		11.5	8.95		8.0	12.98
		11.6	8.5		8.0	13.45
		11.9	7.9		7.9	13.7
		12.2	6.6			
		12.5	5.9			
Run 4		8.6	12.95		11.5	9.1
		9.1	12.15		10.9	9.9
		9.7	11.6		10.2	10.7
		9.9	11.25		9.9	11.25
		10.3	10.7		9.3	11.65
		10.85	10.0		9.1	12.3
		11.5	9.2		8.6	13.0
		11.8	8.1			
		11.9	8.1			

Table 7. Test No. 5.

T_1 Avg: 111.5° C (Act.) - 114.8° C = 238.6° F Barometer: 14.34 psia

$P_{saturation}$: 24.34 psia Date: 7-25-52

P_1 (psig)	P_2 (psig)	T_1 (°C)	Flow (cm)
13.0	11.0	111.0	8.1
13.0	10.0	111.0	9.6
13.0	9.8	111.0	9.9
13.0	9.0	111.5	11.25
13.0	8.5	112.0	11.3
13.0	7.8	112.0	11.5
13.0	8.2	112.0	11.5
13.0	7.8	110.0	11.5(a)*
13.3	9.8	111.0	10.7(b)
12.9	9.3	112.0	10.7
13.0	9.0	110.0	11.4
13.0	8.8	112.0	12.5
13.2	8.4	112.0	12.5
13.2	8.3	112.0	12.8
13.9	8.6	111.0	12.8
14.0	8.5	111.5	13.0
13.0	8.1	112.0	11.7
14.0	10.6	111.0	11.5
13.9	11.0	111.0	9.05
14.0	12.8	110.5	7.4
14.1	13.0	111.0	7.4

*Test discontinued at (a) because of unsatisfactory temperature control. Test continued at (b).

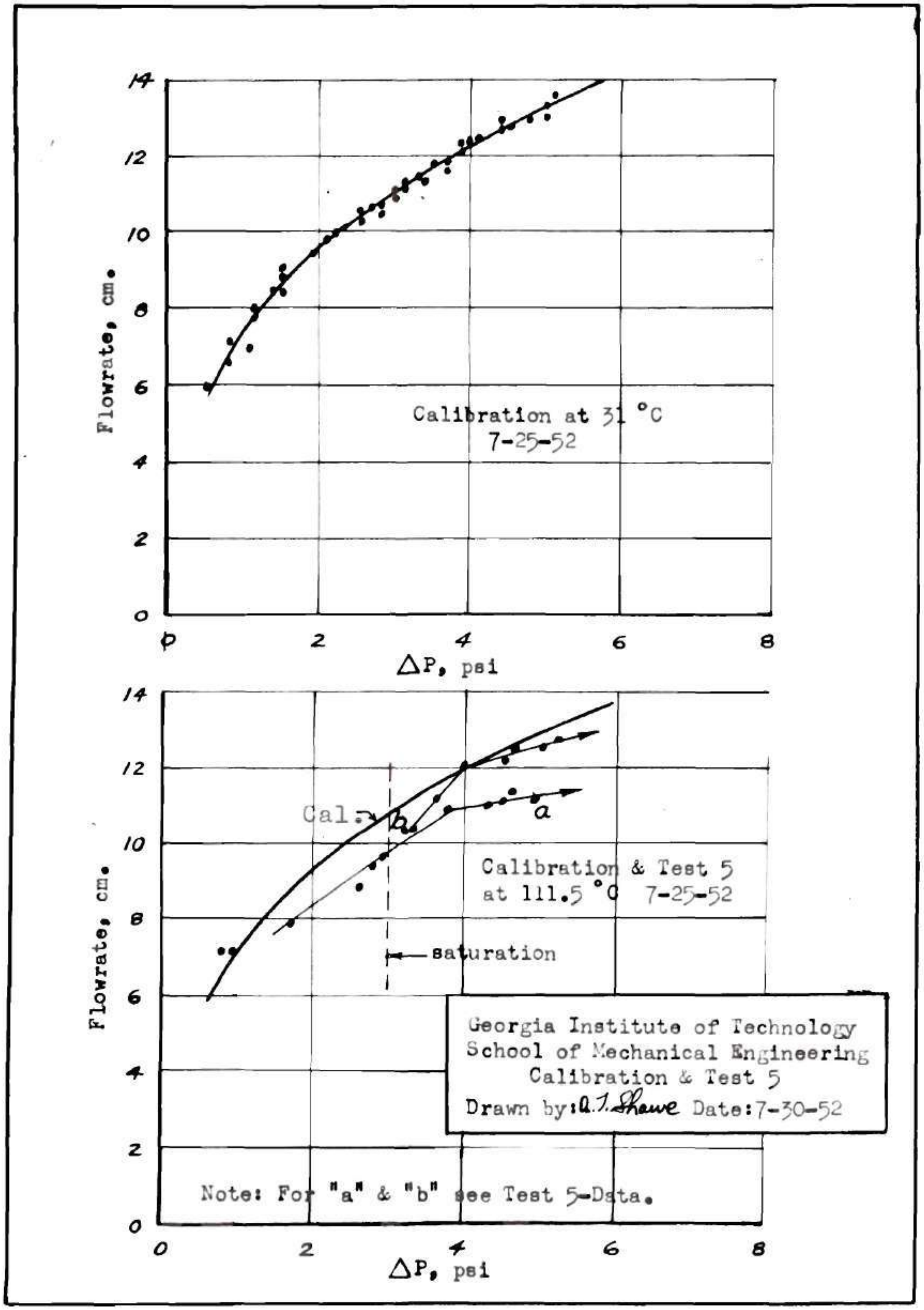

14
12
10
8
6
4
2
0
Flowrate, cm.
Calibration at 31 °C
7-25-52
0
2
4
6
8
ΔP, psi
14
12
10
8
6
4
2
0
Flowrate, cm.
Cal.
b
a
Calibration & Test 5
at 111.5 °C 7-25-52
saturation
Georgia Institute of Technology
School of Mechanical Engineering
Calibration & Test 5
Drawn by: A. T. Shewe Date: 7-30-52
Note: For "a" & "b" see Test 5-Data.
0
2
4
6
8
ΔP, psi

Figure 12

Table 8. Flow Calibration for Tests Nos. 6, 7, 8, 9.

$T_1 = T_2 = 32^\circ$ C

Date: 7-28-52

P_1 (psig)	P_2 (psig)	Flow (cm)	P_1 (psig)	P_2 (psig)	Flow (cm)
13.3	12.5	8.13	13.3	9.5	12.9
(held	11.8	9.0	(held	10.15	11.85
constant)	11.4	10.1	constant)	11.7	9.4
	10.5	11.1			
	10.05	12.0			
	9.7	12.5		9.0	13.8
	9.1	13.2		10.0	11.9
	9.05	13.65		11.5	9.4
	8.9	13.7		12.0	8.4
	8.95	13.65		12.5	7.5
	9.5	12.95		11.2	10.55
	9.95	12.3		10.2	11.8
	10.3	11.4		9.6	12.7
	10.9	10.5		9.0	13.8
	11.5	9.7			
	11.7	9.3			
	12.0	8.75			
	12.5	7.7			
	12.5	8.2			
	11.8	9.3			
	11.3	10.0			
	10.6	11.3			
	10.2	12.1			
	9.1	13.2			
	8.9	13.75			

Table 9. Test No. 6.

T_1 Avg: 111.0° C (Act.) = 114.4° C = 237.86° F Barometer: 14.25 psia

$P_{saturation}$: 23.98 psia Date: 7-28-52

P_1 (psig)	P_2 (psig)	T_1 (°C)	Flow (cm)
13.3 (held constant)	11.5	111	9.5
	11.0	110	10.2
	10.5	111	11.1
	10.0	111	11.8
	9.5	111	12.6
	9.0	112	13.0
	8.5	111	13.5

Table 10. Test No. 7.

Conditions same as for Test No. 6

P_1 (psig)	P_2 (psig)	T_1 (°C)	Flow (cm)
13.3 (held constant)	11.	111	10.4
	10.5	111	11.2
	9.9	111	11.5
	9.5	111.5	12.7
	8.8	111	13.2
	8.5	111	13.5

Table 11. Test No. 8.

Conditions same as for Test No. 6

P_1 (psig)	P_2 (psig)	T_1 (°C)	Flow (cm)
13.3 (held constant	10.5	111	11.2
	10.0	110	12.1
	9.5	111	13.0
	9.0	112	13.4
	8.5	111	13.9

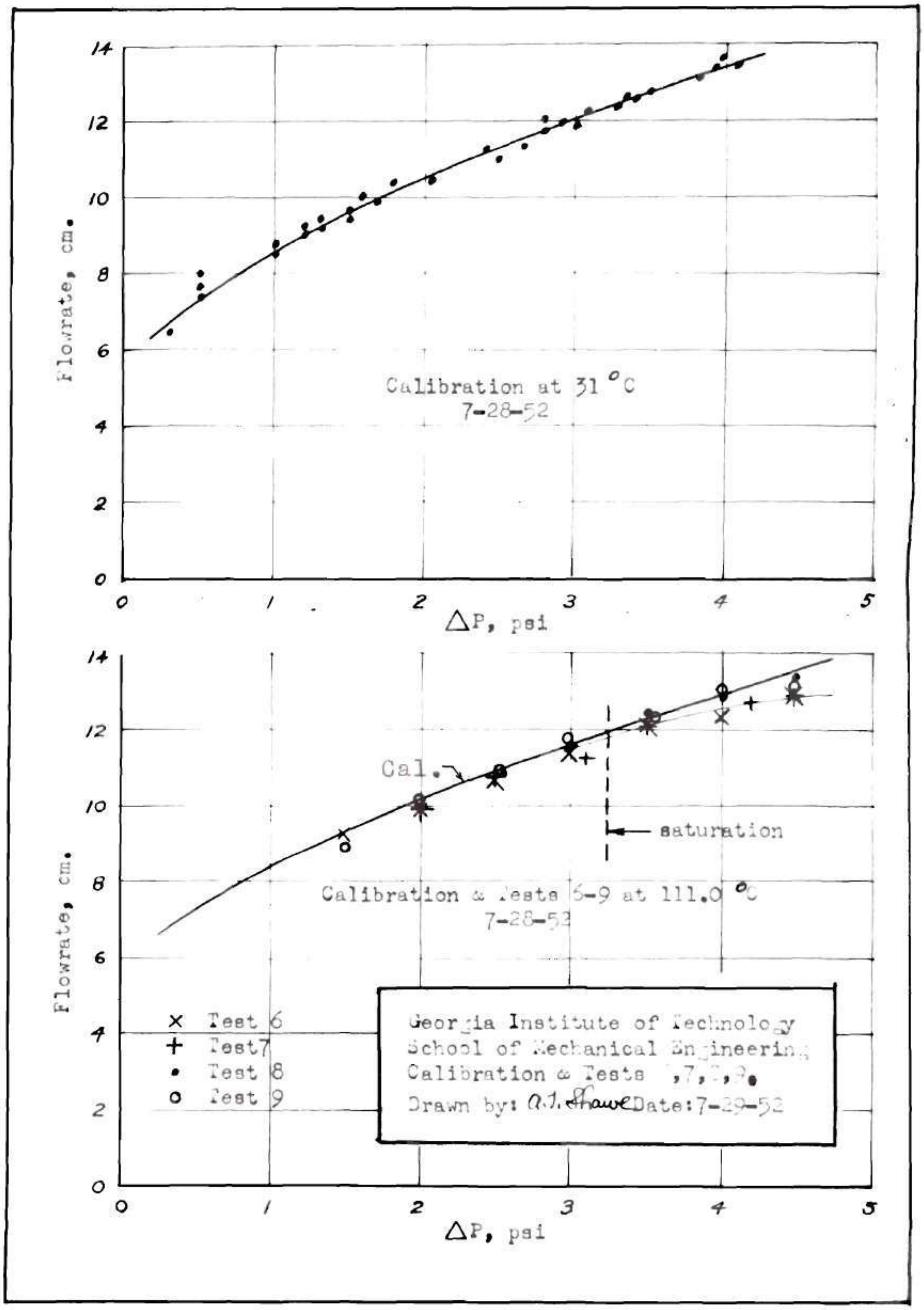
Table 12. Test No. 9.

T_1 Avg: 111.5° C (Act.) = 114.9° C = 238.8° F   Barometer: 14.2 psia

$P_{saturation}$: 24.35 psia   Date: 7-29-52

P_1 (psig)	P_2 (psig)	T_1 (°C)	Flow (cm)
13.3 (held constant	11.5	111.5	9.4
	11.0	111.5	10.35
	10.5	112	11.4
	10.0	111.5	12.2
	9.5	111	12.8
	9.0	112	13.5
	8.5	111	13.6

Photographs were made during this run.



Flowrate, cm.
Calibration at 31 °C
7-28-52
ΔP, psi
Cal.
saturation
Calibration & Tests 6-9 at 111.0 °C
7-28-52
× Test 6
+ Test 7
• Test 8
o Test 9
Georgia Institute of Technology
School of Mechanical Engineering
Calibration & Tests 6,7,8,9.
Drawn by: A.J. Shawe Date: 7-29-52

Figure 13

APPENDIX B

SAMPLE CALCULATIONS

SAMPLE CALCULATIONS

The following sample calculation is for the third line of data, Test No. 1. For accuracy, the same procedure is followed in all tests.

Calibration correction.--

$$P_1 - P_2 = 30 - 20 = 10 \text{ psi} = \Delta p$$

$$\text{Flowrate, cm}_{126.6^\circ \text{ C}} = \text{Flowrate, cm}_{32^\circ \text{ C}} \sqrt{\frac{V_{32^\circ \text{ C}}}{V_{126.6^\circ \text{ C}}}}$$

$$\text{Flowrate, cm}_{32^\circ \text{ C}} = 5.63 \quad \text{(Figure 10)}$$

$$V_{32^\circ \text{ C}} = 0.01610^*$$

$$V_{126.6^\circ \text{ C}} = 0.01709^*$$

$$\therefore \text{cm}_{126.6^\circ \text{ C}} = 5.63 \sqrt{\frac{0.01610}{0.01709}} = 5.45 \text{ cm}$$

Data correction.--

$$5.0 \sqrt{\frac{0.01610}{0.01709}} = 4.85 \text{ cm}$$

---

*Keenan and Keyes, Thermodynamic Properties of Steam.

APPENDIX C

APPARATUS

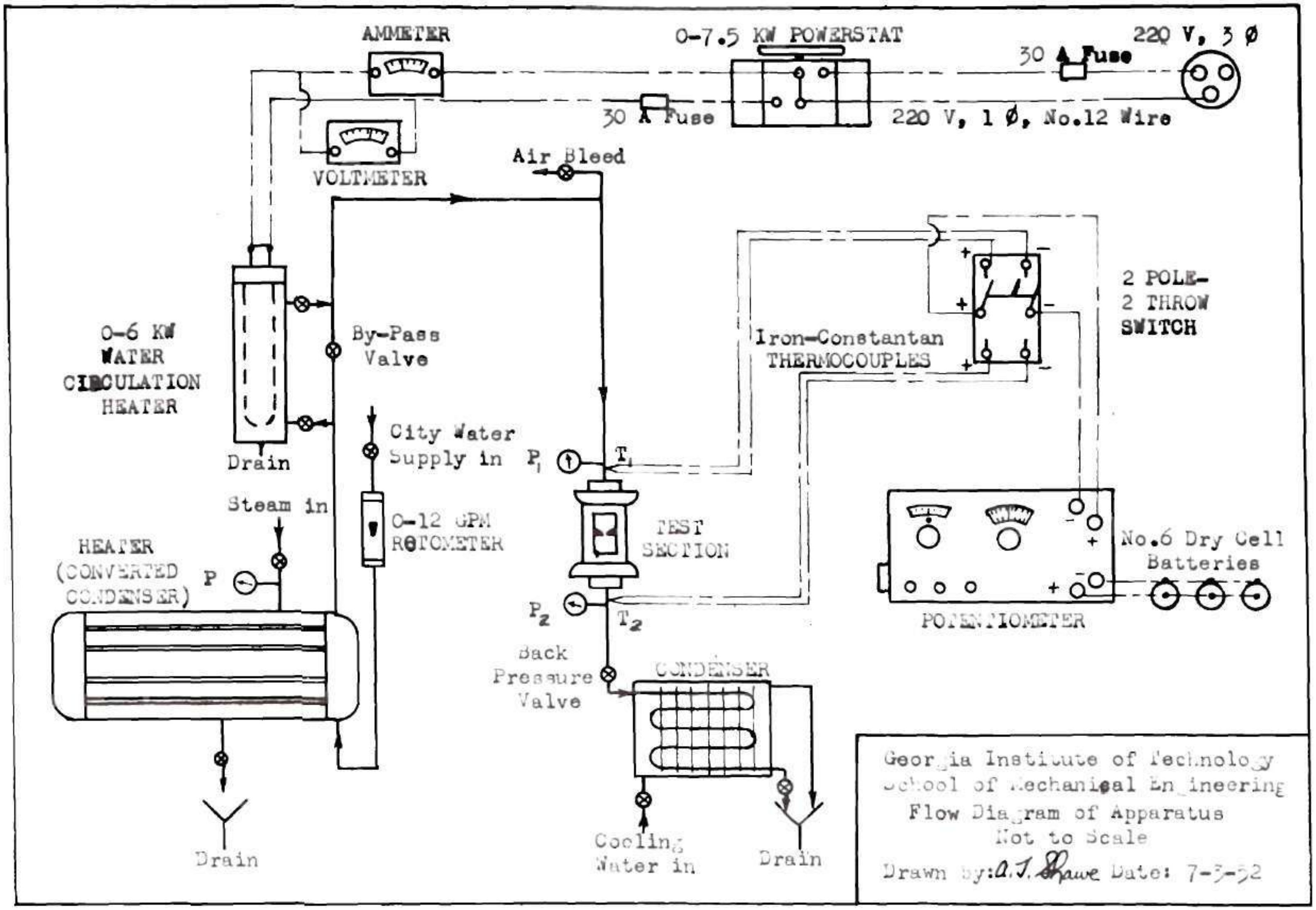
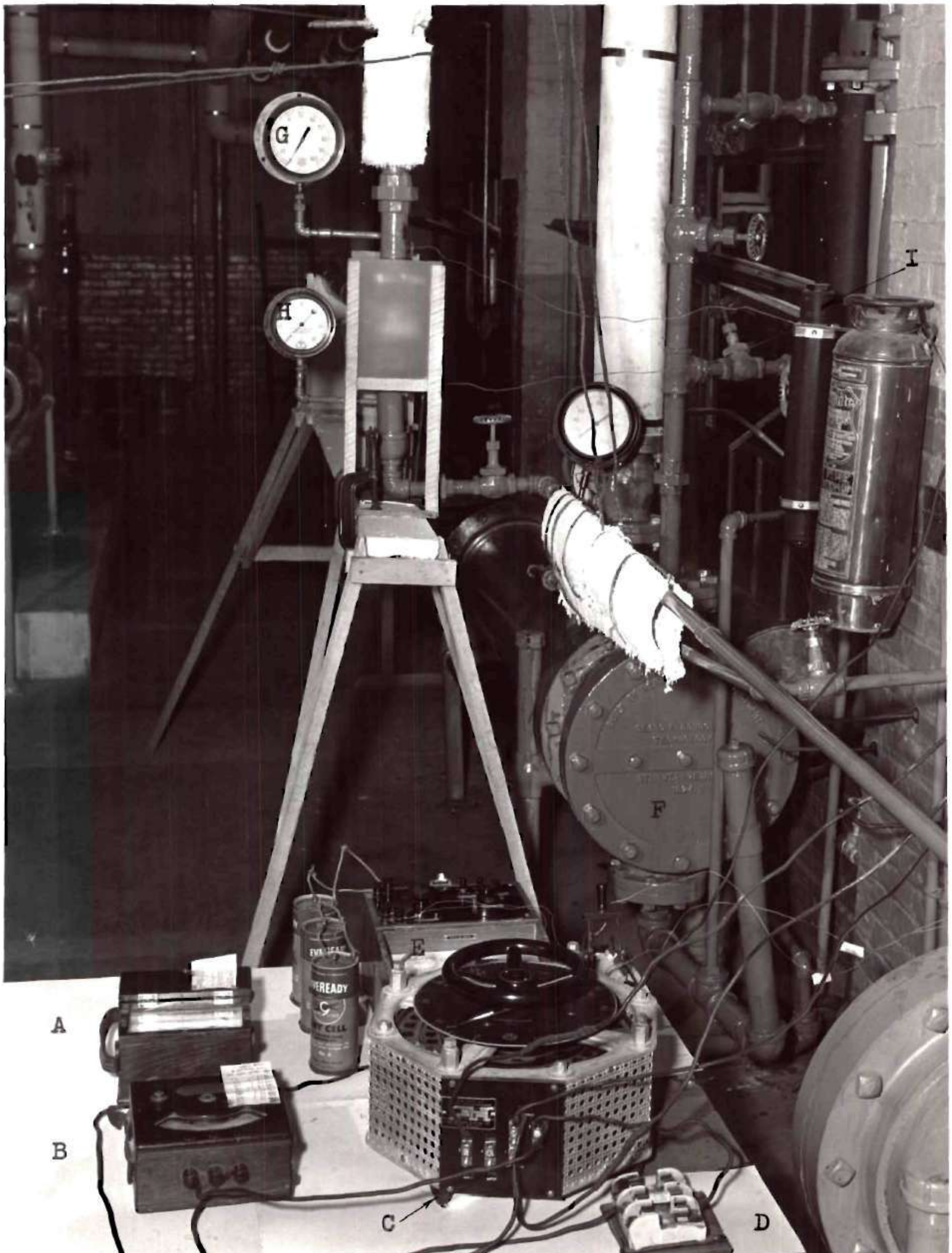

AMMETER
0-7.5 KW POWERSTAT
220 V, 3 Ø
30 A Fuse
30 A Fuse
220 V, 1 Ø, No.12 Wire
VOLTMETER
Air Bleed
0-6 KW WATER CIRCULATION HEATER
By-Pass Valve
Iron-Constantan THERMOCOUPLES
2 POLE-2 THROW SWITCH
Drain
City Water Supply in
Steam in
0-12 GPM ROTOMETER
TEST SECTION
HEATER (CONVERTED CONDENSER)
No.6 Dry Cell Batteries
POTENTIOMETER
Back Pressure Valve
CONDENSER
Drain
Cooling Water in
Drain
Georgia Institute of Technology
School of Mechanical Engineering
Flow Diagram of Apparatus
Not to Scale
Drawn by: A.J. Shawe Date: 7-3-52

Figure 14



A Ammeter
B Voltmeter
C Powerstat

D Fuse
E Potentiometer
F Heater (Cond.)

G P_1
H P_2
I Rotometer

Figure 15. Picture of Apparatus

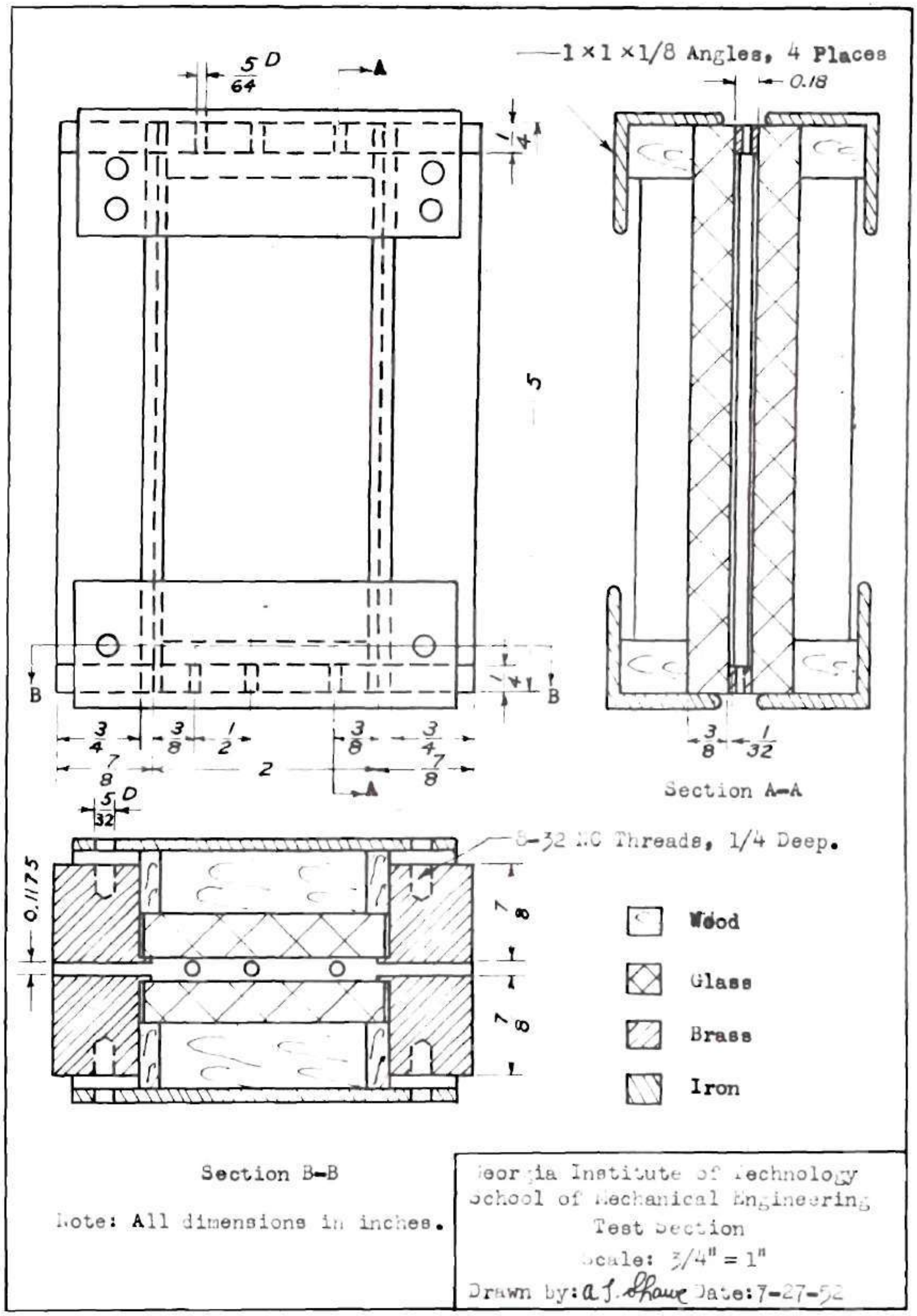

1 × 1 × 1/8 Angles, 4 Places
0.18
5/64 D
A
1/4
5
B
3/4
3/8
1/2
7/8
2
Section A–A
5/32 D
0.1175
8–32 NC Threads, 1/4 Deep.
7/8
Wood
Glass
Brass
Iron
Section B–B
All dimensions in inches.
Test Section
Drawn by:
Date: 7-27-52

Figure 16

Figure 17. Test Section Assembled

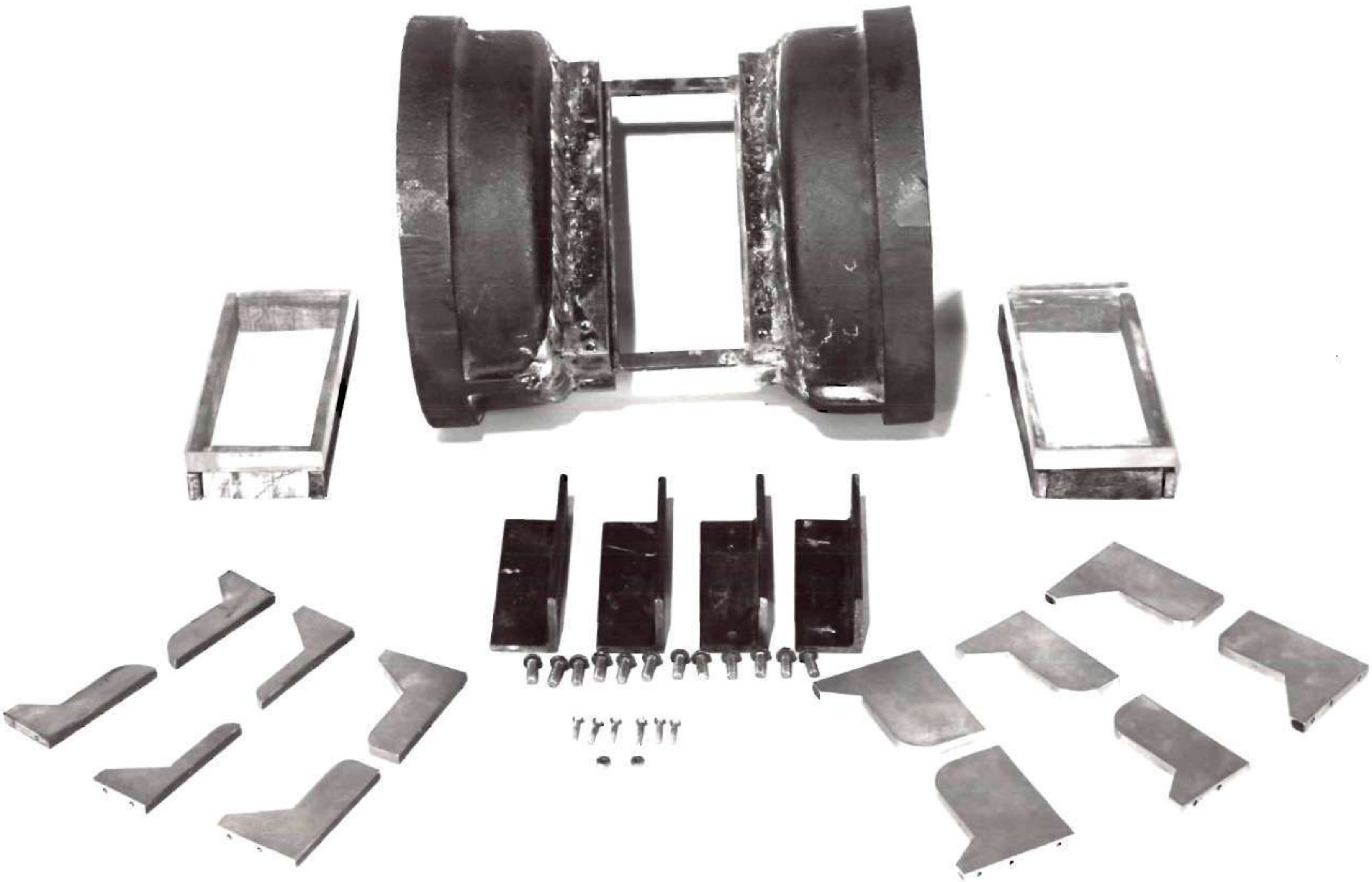


Figure 18. Test Section Unassembled

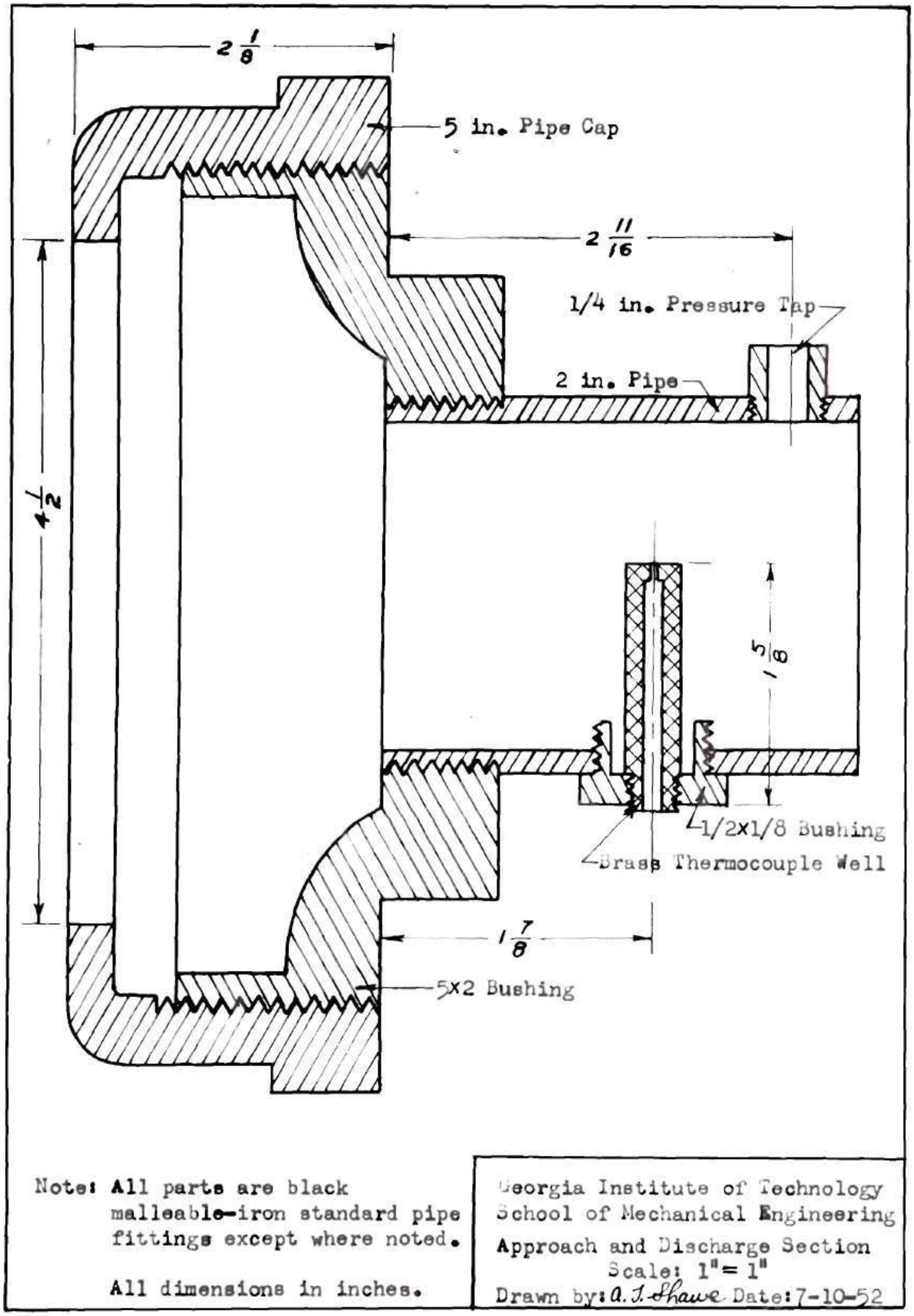
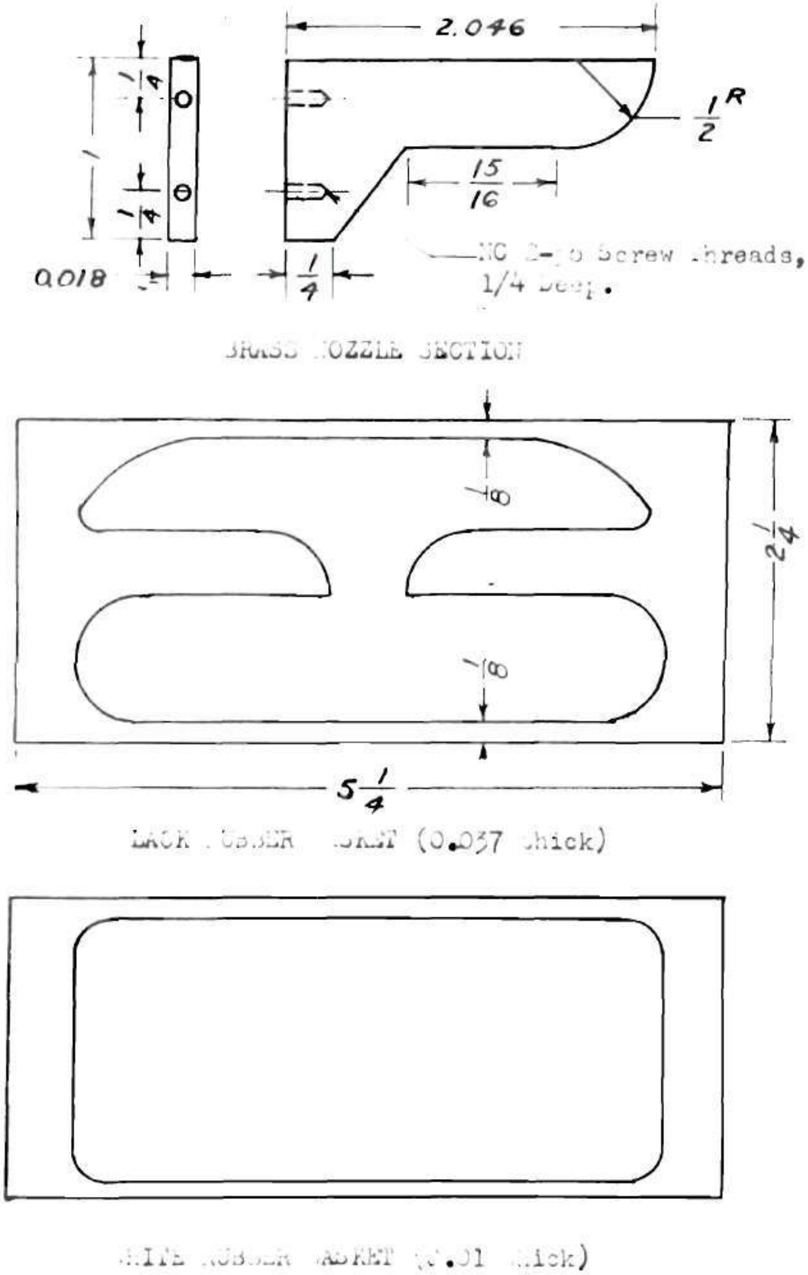

2 1/8
5 in. Pipe Cap
2 11/16
1/4 in. Pressure Tap
2 in. Pipe
4 1/2
1 5/8
1/2x1/8 Bushing
Brass Thermocouple Well
1 7/8
5x2 Bushing
Note: All parts are black malleable-iron standard pipe fittings except where noted.
All dimensions in inches.
Georgia Institute of Technology
School of Mechanical Engineering
Approach and Discharge Section
Scale: 1" = 1"
Drawn by: A. J. Shawe Date: 7-10-52

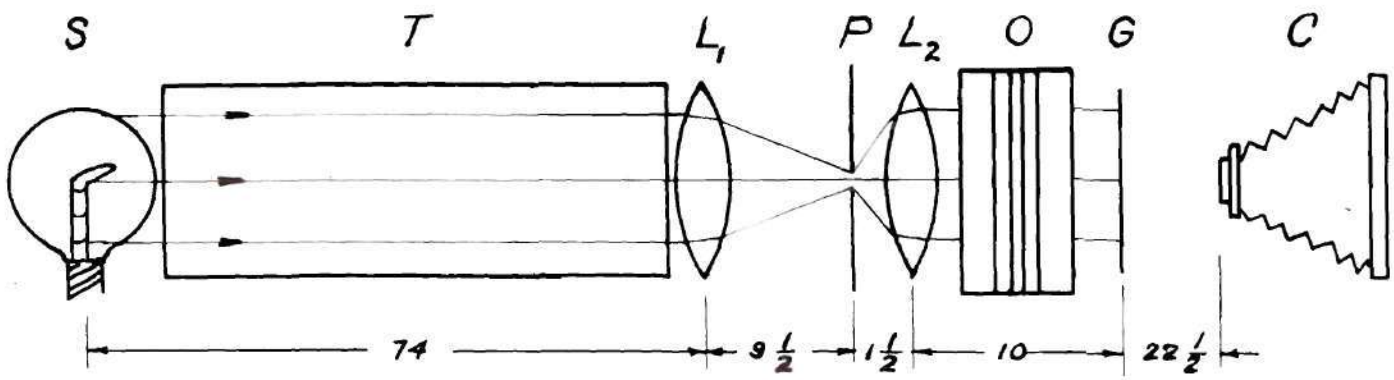
Figure 19



Note: All dimensions in inches.
Two of each required.

Georgia Institute of Technology
School of Mechanical Engineering
Nozzle & Gasket Design
Not to Scale
Drawn by: A.J. Shaw Date: 7-20-52

Figure 20

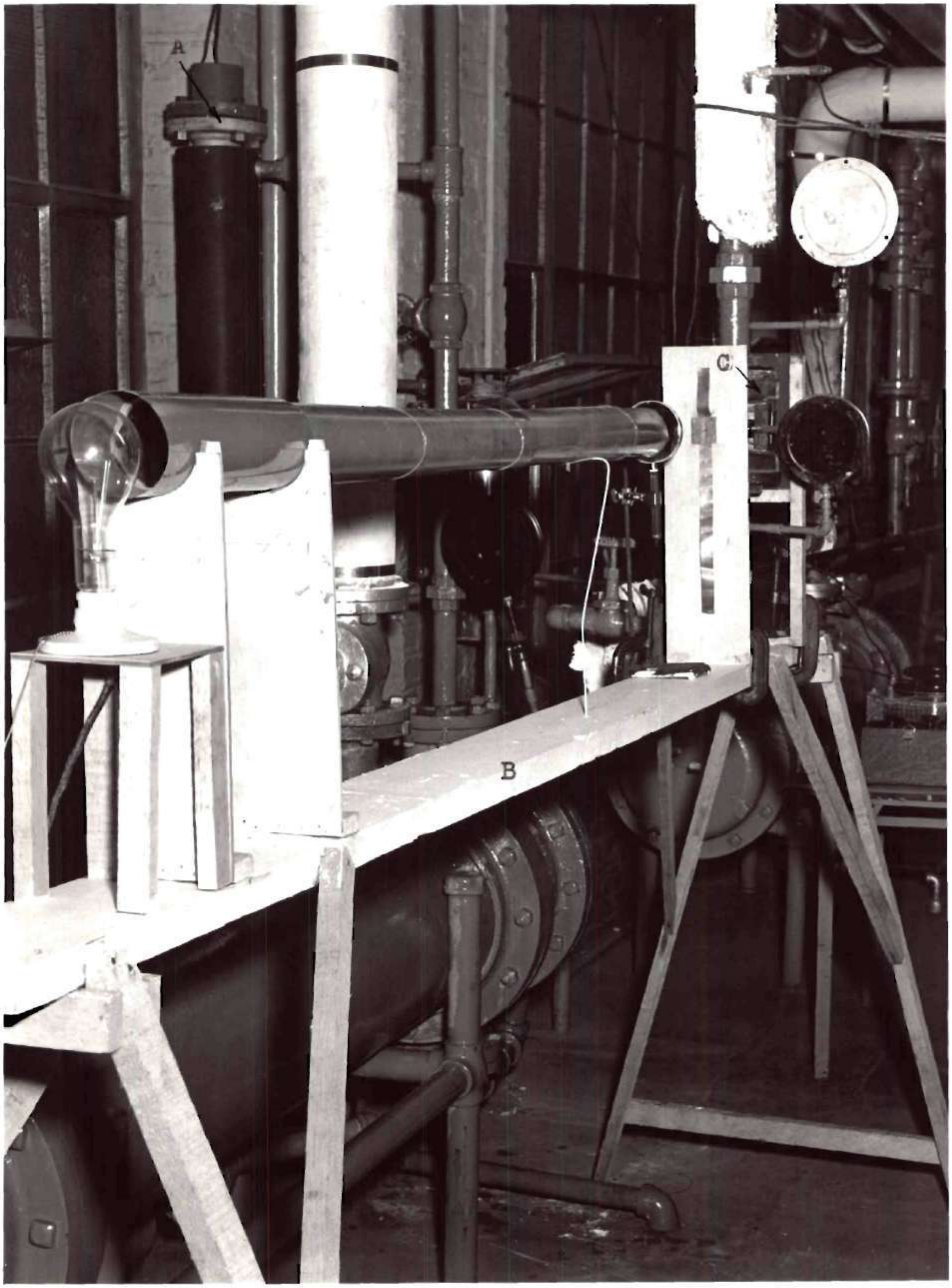


S	Light Source	L	Collimating Lens
T	Tubing	O	Object
L	Camera Lens	G	Ground Glass Screen
P	Point Light Source	C	Camera

Note: All dimensions in inches.

Georgia Institute of Technology
School of Mechanical Engineering
Shadowgraph Apparatus
Not to Scale
Drawn by: A. S. Shaw Date: 7-25-52

Figure 21



A Electric Heater B "Horse" C Test Section

Figure 22. Picture of Shadowgraph & Equipment

APPENDIX D

CALIBRATION CURVES

Table 13. Calibration of Discharge Gage.

Type: Bourdon Tube Range: 0-30 psig

Manufacturer: Kewanee Boiler Corporation

True Pressure	Actual Pressure
0.0	0.0
5.0	5.0
10.0	10.0
15.0	15.1
20.0	20.2
25.0	25.2
30.0	30.0

Table 14. Calibration of Inlet Gage

Type: Bourdon Tube Range: 0-100 psig

Manufacturer: Crosby Steam Gage and Valve Company

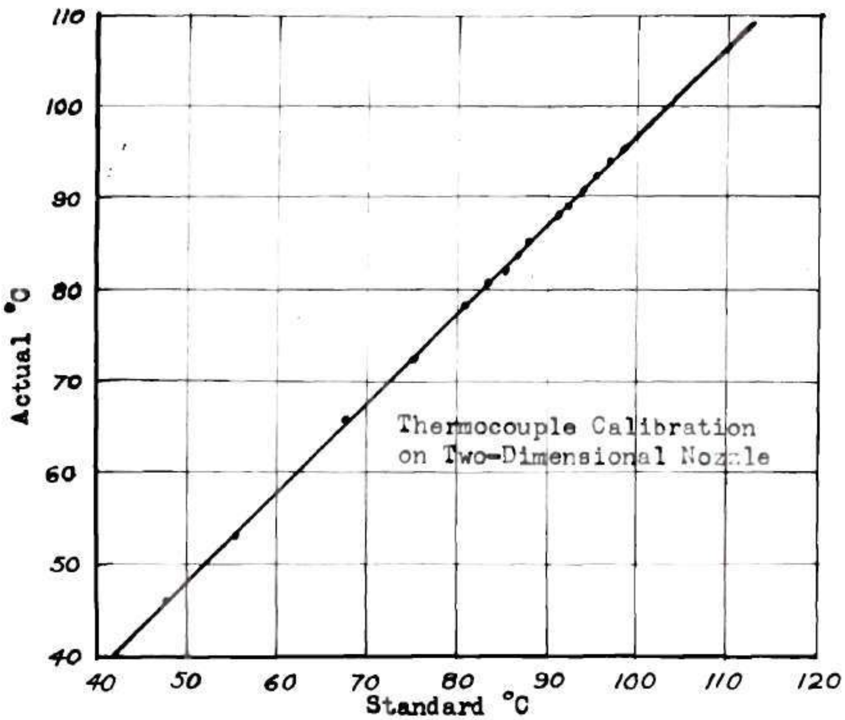
True Pressure	Actual Pressure
0.0	0.0
5.0	5.2
10.0	10.4
15.0	15.3
20.0	20.6
25.0	25.5
30.0	30.0
35.0	35.5
40.0	40.0
45.0	45.0
50.0	50.0
55.0	55.5
60.0	60.0

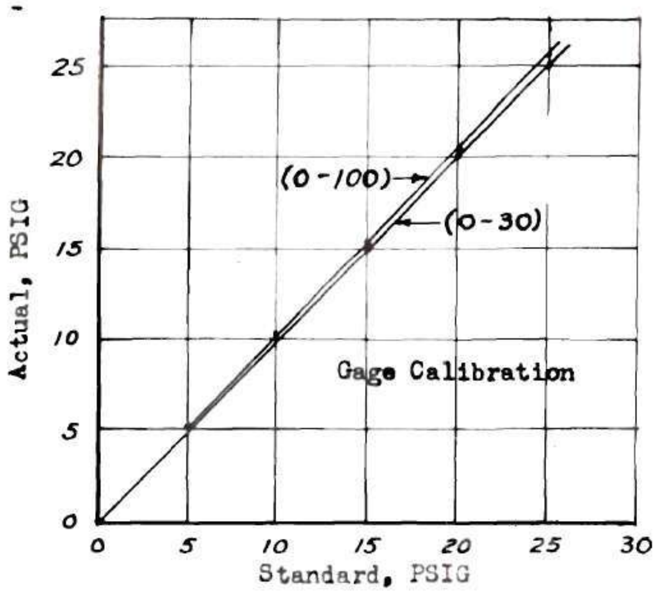
Table 15. Calibration of Temperature-Recording Apparatus

Type: Iron-Constantan Range: 0-800° C

Manufacturer: Leeds and Northrup Company

Standard °C	Actual °C
47.5	46.0
55.5	53.0
67.5	66.0
73.0	71.0
75.0	72.5
81.0	78.5
83.5	81.0
85.0	82.0
86.5	83.8
88.0	85.5
91.5	88.5
92.0	89.0
94.0	91.0
95.0	92.1
98.0	95.5
97.0	94.0





Note: Thermocouple calibration met standard requirements for Tests No. 1,2,3,&4.

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Equipement Calibration
Drawn by: A. J. Shwe Date: 7-29-52

Figure 23

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